INTERNATIONAL DESIGN CONFERENCE - DESIGN 2008
Dubrovnik - Croatia, May 19 - 22, 2008.

A NEW KNOWLEDGE BASED APPROACH THE REVERSE ENGINEERING OF A PRODUCT

A. Durupt, S. Remy, G. Ducellier and W. Derigent

Keywords: knowledge product, design skeleton, reverse engineering

1. Introduction

Reverse engineering (RE) is a domain of current interest. It appears that nowadays, companies, organisation and suppliers need to manufacture old parts or products they use everyday. As an example, RE is massively used by the US army (Army research office virtual parts engineering research initiative, [VPERI, 2003]) for the maintenance of their legacy part because the documentation about the components may be unavailable, incomplete, or in form incompatible with modern computer aided design and manufacturing software. In the forging industry, people have to manufacture new tools for old parts. Also, suppliers have to produce parts from the prototype of a customer.

Regarding the current (RE) approaches and according to users, the results obtained are not good enough because geometric models rebuilt are generally frozen (parametric surface approaches) or not re-usable (meshed surface approaches). Consequently, the possibility of re-engineering or re-design does not exist. For example, in a meshed model, a hole has neither diameter nor axis. Moreover, apply constraint of a parallelism or a fillet between two faces is impossible. With the "surface/solid based approaches", the 3D point cloud of the original object is changed into a surface model or a solid model. The resulting model is as useless as a meshed model regarding to re-design possibilities. Surface models or solid models can be also obtained from point clouds using CAD solution. In this case, it is possible to obtain a model that enables re-design approach but it is a very long set of geometric operations.

This paper proposes a new research direction which takes into account knowledge about the lifecycle of the original product. Into real CAD model, designers put data about expert knowledge (with parameters and relationships), the manufacturing process, the function of the product, etc… A geometric approach is not sufficient for obtaining such a product model. The knowledge dealing with the product, its lifecycle and its environment have to be considered as well as the geometric appearance.

Thus, this research direction proposes to formalise this knowledge and to semi-automate the rebuilding methodology. Objectives are to obtain a real CAD model with a tree structure of features called functional and structural skeleton. The originality approach is the merging between a classical geometric approach (point cloud segmentation and features data extraction) and a knowledge based approach (functional and structural skeleton).We believe that knowledge extraction step only is sufficient for obtaining the skeleton model. The segmentation step allows to measure the parameters (Diameters, lengths, etc…) and to fit skin of the model on the CAD model.

This paper is organised as follow, section 2 presents a state of the art on the currently segmentation techniques and the knowledge could be revolving around the part based on several project references. Section 3 presents how collect the knowledge by techniques and concepts will be used. Section 4 presents conclusion and how connect the geometrical recognition and the knowledge steps. Each section will be illustrated by the use case of the journal cross of a Peugeot 403.

2. The State of the art

2.1 Segmentation techniques

Segmentation is a complex iterative process to logically divide the original point cloud into a set meaningful subsets, one for each natural surface, such that each subset contains just those points sampled from a particular natural surface. There are diverse methods for segmentation, which differ according to the measurement quality, quantity of points, geometric characteristics of the part and amount of human interaction required. The main types of segmentation techniques are Range Image Segmentation and Range Data Segmentation (2D type). Many works about segmentation are listed in [Mohib 2006].

The 3D second type based on the segmentation of a 3-D digitized data (Point Cloud) is more interesting in the research context. These types of point clouds are obtained using 3D sensors. These sensors can be from several types (structured light, laser triangulation, contact…) and are often integrated on several devices (Coordinate Measuring Machine, 3D measurement arm…). These point clouds are sets of unorganised points representing 3D objects. We suggest an overview of several segmentation techniques. [Patané 2002] proposed an approach for Edge-based segmentation and extraction of feature lines based on a multi-resolution representation and analysis of the scan data. In this approach, based on a sequence of local updates, the point cloud is organized according to a multi-resolution hierarchy. The application domain of this approach is defined by scan lines. This approach is characterized by three phases; a) multi-resolution data modelling, b) A scale and a geometry classification based on form feature similarity, and c) a two step line by line detection phase and segmentation. [Woo 2002] introduced a different Edge-based segmentation approach that uses an Octree-based 3-D grid splitting process. An iterative subdivision of cells is done based on the normal values of points, and the region growing process to merge the divided cells into several groups. A triangulation method is used in estimating the point normal. The input for this algorithm is a well organized point cloud based on the scan line from a strip type laser scanner. [Benko 2004] used a non-iterative approach "Direct Segmentation" based on the fact that it is possible to compute local characteristic quantities (e.g. normal direction) within the interior face. This characterizes the planarity of the point neighbourhood. Then, a second order algebraic surface is fitted to surrounding points in the neighborhood. However, direct segmentation produces disjoint regions, each of which is approximated by a simple analytic or swept surface. An extension to this work is presented in [Benko 2004]. As segmentation of surfaces sharing sharp edges is easy, they present algorithms including tests to cut surfaces sharing smooth edges. These tests are based on statistical similarity.

Thus, the scientific literature is composed of lot of segmentation techniques and to research a new technique path add a new technique among widely others. For these reasons, we explore another direction which taking into account the product knowledge in order to deduce most important design parameters (diameter, radius, for example). In the following part, we present several references representatives which show the type of knowledge.

2.2 Definition of the knowledge and what is the knowledge?

RE begins with a manufactured part and produces a geometric model. We believe that redesign is possible as soon as the original design intents are known [Benko 2004]. Our goal is to deduce the design intents of the part. [Mohagheh 2006] in a study case of Turbine Blade combined Reverse engineering process which at the same time gets information from two different sources : The conventional way (to measure the model) and reviewing the design aspects. For example, the Analysis of the process reveals geometrical aspects: when using a mould to create a part, the side faces are usually slightly rotated in order to ensure that the part can easily be removed from the mould. The process analysis is not the study object, their concept are based on the feature recognition that is a purely geometric approach. The feature based methods are often characterized as knowledge based and use any knowledge and information that are related to design intent. For example, the REFAB (Reverse Engineering-FeAture-Based) project, by [Thompson 1999], is a human interactive system where the user selects the feature that are predefined in a list. Then, he chooses where it is located in a 3D point cloud. This system supports constraints such as parallelism, concentricity etc… which allow a real possibility of redesign. Our approach is different, it consists in making analysis of a part in order to reveal the presence of driving design parameters and to structure them in a CAD tree to obtain the functional and structural skeleton. This skeleton model offers a real possibility to change the model using the parameters. For example, a skeleton of a bore feature is represented by the parameters: Section and axe (Material flow) of a bore.

We can notice in the scientific literature that they are two types of knowledge. [Bespalov 2005] presents several distinctive benchmark datasets for evaluating techniques for automated classification and retrievals CAD model. These datasets include two datasets of industrial CAD models classified based on object function and manufacturing process. The first classifies into (1) prismatic machined parts and (2) cast machined part. The second classifies the function by seven groups of models (Linkage arms, Housing, Brackets, Nuts, Gears, Screws and Springs). A VPERI [VPERI 2003] (Virtual Parts Engineering Research Initiative) project was created by the US Army Research Office in order to provide the vision, strategy, and engineering to help solve legacy systems problem. This latest owns and operates many complex electro-mechanicals that were designed 25 to 50 years ago. Because of the cost of replacement, these systems may have to be used for decades to come, well beyond their intended design life. Maintenance requires spare parts, in many cases, the original manufacturers are no longer around to provide them.

Hence, Army needs a comprehensive plan to determine how best to prolong the life of these legacy systems and, in some cases, new technology to reverse engineers critical parts. Manufacturing for old systems can be difficult because documentation about the components may be unavailable, incomplete, or in a form incompatible with modern computer aided design and manufacturing software. For them, just the knowing of the geometric shape and size is necessary but not sufficient to reproduce the part. The another knowing such as Material specification, heat treatment, surface treatment, surface finish and tolerances must be known. Moreover, availability of new materials, manufacturing methods favour the choice to improve the design and the motivating factors must be cheaper material of cheaper production cost etc. Moreover, they consider that in some cases, it might be to ignore the original part and to re-design completely or to replace it with an equivalent contemporary standard device. Before, the performance requirements, space/weight constraints, mechanical/electrical connections, flow and potential variables at the connections, signal types/magnitudes must be extracted from the existing system by physical testing. Thus, this first reference shows a class of product knowledge, there is a functional specification with, for example the mechanical/electrical connection and signal types/magnitudes.

The RID (Reverse Innovative Design) methodology [Xiuzi,2007], in a product design context, which combines the benefits of two worlds, the design intent and knowledge represented by features with their associated definition parameters and the flexibility of shape deformation. The product definition parameters will be obtained based on the feature skeletons extracted from the mesh. The skeleton obtained is issued of the segmentation results.

[Bernard 2006] suggests an approach for redesigning or the reconstitution of an old mechanism and tries to answer at this question “how to prolong longevity of the technical information of collection, archives and heritages sites?” In this approach, authors advance that knowledge has to be capitalised from the Functional Diagram Block of APTE method. Two knowledge types are distinguished: Characteristics (internal flow design only: functional and structural); the outside world (context socio-technical environment etc).

Among this several references, we can distinguish two types of knowledge. It concerns the functional and manufacturing context.

3. Collection of knowledge

A CAD model contains expert knowledge (Parameters, relations, attributes and design features) given by a designer. This knowledge is domain-related and could concern for instance the product mechanical functions or its manufacturing process. In a reverse engineering context, numerous product details are known. We will qualify this knowing as "product knowledge". To take into account this knowledge and its interpretation will allow to help the geometric feature detection during the reconstruction phase. It will confirm (or not confirm) the detection of certain surface types and ease the determination of driving and led parameters. In fact, a CAD model is not only a geometrical feature but a technological feature too. To ease the reconstruction process, and to determine parameters (which are knowledge parts), we need to know in an accurate way what the environment of our product is, and what its functions are. We truly believe this product-related knowledge will dramatically help the reconstruction process.

This step consists to list knowledge related to the part by taking into account of its life cycle and its environment. From our point of view and several references in section 2.2, the knowledge can have two types: On the one hand, the manufacturing knowledge (foundry, machining…) and, in addition, the finality of part by the study of the functionalities it ensured. Consequently, firstly, we restrict our study to two contexts: functional context and process context. We assume that both are known or easement deduced.

Firstly, our work is to assist a CAD user in order to extract knowledge product useful to deduce a class of design driving parameters allowing to build a design skeleton called functional and structural skeleton. This latest is studied in LASMIS (University of Technology of Troyes, France) laboratories by L. Roucoules and J.S. Klein Meyer.

The functional and structural skeleton is based on a concept of skin and skeleton:

The first represent any surfaces through circulate a generalized current:

- Mechanical current (Contact zone between two parts)
- Magnetic current (magnet pole)
- Electrical current

The second represent the material which transmits energy flux between the various skins, it could be:

- A section (for example the section of cylinder.)
- A trajectory material flow (the axe of cylinder)

To summarize, knowledge about the lifecycle (manufacturing process and functional analysis) of the product can be used to justify the presence of features as well as to extract parameters and constraints that link these features with each others. It enables to create a skeleton that will be used to create the CAD model that is more than a simple geometric image of the product.

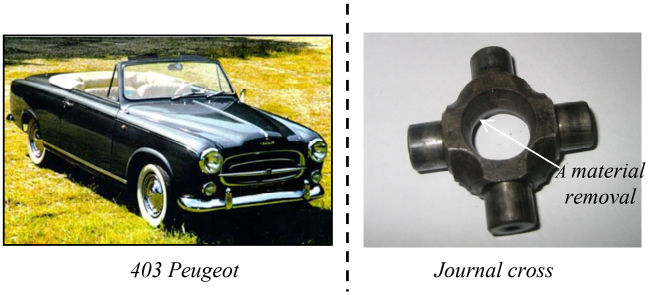
In the next section, we show to illustrate the proposed approach using the case of study of a journal cross of Peugeot 403 (Old French car).

3.1 The manufacturing knowledge

By observation of old parts, the manufacturing of which is extracted is ease to deduce. Indeed, mould, casting extraction etc… leave traces on surfaces such as line of joint for mould process. Moreover, manufacturing concern certain material. Thus, in this part, we show that manufacturing knowledge imposes geometrical shapes. "Rules trade" of a different process lead to different shapes and particular geometrical characteristics important for the part manufactured. The latest can be extracted of procedure manuals or trade experiment. A listing, by audit for example, will allow to integrate manufacturing rules extracted from usual manufacturing processes. For example, a prismatic milled part could have a large plane surface which corresponds to a fixture. Width, length, perimeter and area can be possible driving parameters. Another example, a cast part has drafted surfaces. Draft angles can also be driving parameters.

The concept above is illustrated by the use case of Peugeot 403's journal cross.

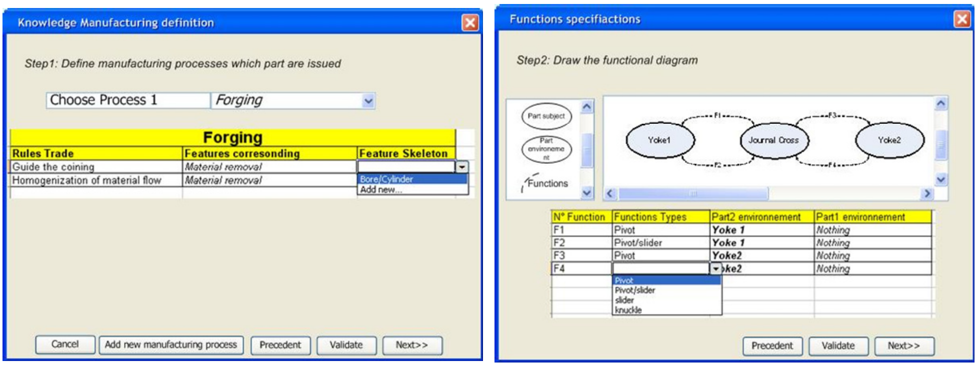
On the figure 1, The hole (Material removal) presence reveals that part was manufactured by forge process. It allows to guide the coining and the homogenization of the material propagation. Thus, the interpretation of this knowledge reveals the presence of cylinder which corresponds to a material removal. The driving parameters are the diameter and the length of the cylinder.



403 Peugeot *Journal cross*

Figure 1. The material removal in the journal cross

On figure2.a, we suggest an interactive interface, where the CAD user informs, after analysis of the part, one or more scenarios of the manufacturing process. For each manufacturing process, the CAD user consults the rules trades saved in a database. Each rules trade corresponds to one or more features (in this use case, a hole). The CAD user selects or adds the best feature among a list of class features. Hence, the functional and structural skeleton is represented by the section of this cylinder which are commanded be the diameter and the trajectory material flow by the cylinder axe which are commanded by the length of the cylinder. This first step implicates to provide a list of skeleton features which corresponds manufacturing process currently used.
The second step consist in extracting knowledge of functional specifications of the part



(a) (b)

Figure 2. An example of interface for "knowledge extraction"

3.2 The functional specifications

A machine/system/part is a study case and was designed and manufactured in order to answer a industrial need. Thus, each part ensures one or more known functional specification. Consequently, environment of the system is known. "Environment" and "function" terms highlight the concept of functional analysis, which could ease to reveal the part geometrical information, of course the design parameters.
To date, we believe that the emergence of functional analysis of a product type APTE blocks diagram functional can reveal the mechanical linkage. In a second time or in a perspective, we assume the system will integrate part ensuring magnetic/mechanical/electrics links which environment parts. Hence, we will research a graph type adapted. Here, the journal cross is a mechanical part pure, it

ensure just mechanicals link with parts environment (theYoke1 and the Yoke2). On the figure 2.b, the user draws a graph which corresponds at the “graph linkages”.
For example, one of mechanical functions of a piston is ensured by a pivot linkage with a bore. Consequently, this linkage reveals the presence of cylindrical surfaces. Thus, the driving parameters could be the diameter and length.
In the design product, the skeleton design concept is currently used. In the re-design context, the functional and structural skeleton allow to justify, within manufacturing or specification function point of view, the different features of a part and the constraints which link them.
Consequently, the “product knowledge” will allow to assist the expert CAD user in the revelation of driving parameters. These latest shall to command the section and the trajectory material flow and allow at the final changed the design, in other terms, re-design. “The knowledge product” require to be managed. This management will be made in a TDMS (Technical documentation management system) and the assistance with the user by software interface integrated in a shell of a CAD system.
In the use case of a journal cross, the environment is represented by two yokes. Indeed, we suggest a system solution, based on a functional analysis, which allow to list the environment of the part and to establish relationship between the both. In our study case, environments are the two yokes.
The four functions of functional analysis are to ensure a Pivot and Pivot/Slider between the both Yokes. They reveal the presence of four cylindrical surfaces. Hence, the design driving parameters is diameters and the lengths of each cylinder. The future software interface will assist the CAD user in order to define the constraints and relationship between the features defined above. In this case, axes of the four cylinders are in coaxially 2 to 2 and equals in lengths 2 to 2. Moreover, all diameters are the same values. We assume the several constraints will allow to generate the first functional and structural skeleton in a CAD software. The design tree will be structured in a following way:

- Each feature (skeleton and section) generated in a part file.
- All features with relationships in an assembly file which correspond at the part.

We also assume the future interface proposes to define ease constraints automatically such as coaxially constraint and to generate a pre-assembly file.

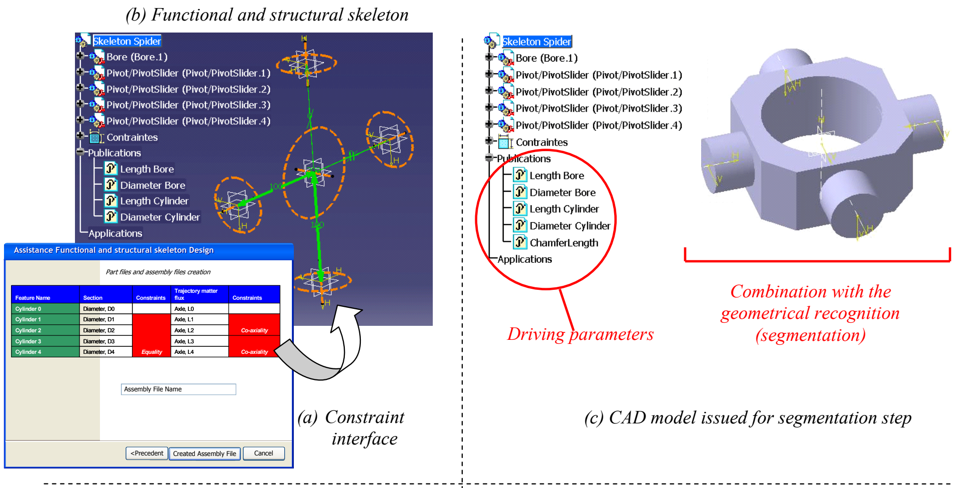


Figure 3. The CAD model with “knowledge extraction”

On the figure 3.a, we show a picture of a future interface in the last step of creation. An user define first constraints and the system generated a pre-constrained assembly file. Indeed, at the moment, we believe that a CAD shell interface is most adapted for the definition of most complex constraints such

as for example angle constraints and parallel constraints. This final step imply to insert, in a system, a class of constraints, we suppose constraints currently used in the CAD software.
On the figure 3.b, user will define manually other constraints and built the completely functional and structural skeleton.
Finally, with the segmentation step, the resulting CAD document considers the entire functional and structural knowledge and geometrical parameters coming from the geometrical approach. Based on this listing of parameters from the "knowledge" step, the system provides measurement functionalities on the geometrical part. Values are assigned to the parameters. Parameters are included in a skeleton at the top of the assembly tree. This skeleton is used as a reference for each part composing the assembly. Each parameter is copied with reference in parts composing the journal cross. The user has to complete the 3D model with surface and volume functions (figure 3.c). For each type of natural surface, the CAD application provides multiple functions of reconstruction. As an example, a cylinder can be created by using an extrusion function, a rotation or a sweep function. In this context, our system proposed a strong interaction with the final user. It proposes a friendly interface for linking functional and structural information, geometrical parameters and CAD functions in order to provide a fully parameterized CAD assembly.

4. Conclusion

RE based on geometrical approach is often frozen and not reusable. In this paper, we focus on the classical design approach adapted to RE issue. In this approach, we define functions of the product based on the interaction of multiple expertises in order to identify and classify the driving parameters.
Each function of the product is organized and stored in a skeleton design called in this paper, the functional and structural skeleton. Based on this skeleton, we suggest a hybrid approach that integrates geometrical and functional aspects. The main goal of this approach is to obtain a complete and fully parameterised CAD model including design intents.
As the first milestone, we propose a prototype software application which answers to the need for integration between geometrical and functional aspects of the part. In the case of study, knowledge interpretation is reduced to a single part. Software solution interface has to be developed to take into account the product assembly.
As the second milestone, a methodology is required to interpret and to manage product knowledge in order to deduce the set of driving parameters and to construct the functional and structural skeleton. This methodology is clearly needed when considering larger assembly or complex parts.
As the third milestone, we develop a solution for connecting a geometrical recognition with the functional and structural skeleton.
The merging between knowledge management and geometrical recognition will enable to build a complete and fully parameterisable CAD model (figure 3.c). Finally, we will propose a software solution as a tool for a knowledge based reverse engineering.

References

Benko, P. Varady, T.,"Segmentation methods for smooth point regions of conventional engineering objects" Computer Aided Design,2004, 36:511-23.

Bernard, A.., Laroche, L., Ammar-khodja, S., and Perry, N.," Impact of New 3D Numerical Devices and Environments on Redesign and Valorisation of Mechanical Systems", Annals of the CIRP,2006, Vol. 56/1/2007.

Bespalov,D.,Yiu Ip,C., Regli,W,C., Shaffer,J., "Geometric and Intelligent Computing laboratory",Department of Computer Science, Department of Mechanical Engineering and Mechanics, college of engineering,Drexel University,Philadelphia,2005,275-286.

Mohaghegh,K., Sadeghi,M,H.,Abdullah,A., "Reverse engineering of turbine blades on design intent", Int J Adv Manuf Technol, Springer-Verlag London, 2006 ,32:1009-1020

Mohib A., Remy S. , ElMaraghy H "Recognition of geometric primitives using medial axis transform." Proceedings of the CIRP Design Seminar 2006, Kananaskis, Canada.

Patané, G., and Spagnuolo,M.,"Multi-resolution and slice-oriented feature extraction and segmentation of digitized data", SM'02 conference, Saarbrucken, Germany,2002, 305-12.

Thompson, W., Owen, J., De St Germain, H., Stark, S., Henderson, T., "Feature based reverse engineering of mechanical parts" IEEE Transactions on Robotics and Automation, 1999; 15(1):57-65.

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

Woo, H., Kang, E., Wang, S,. and Lee, K.," A new segmentation method for point cloud data", International Journal of machine tools and manufacture,2002, 42:167-78.

Xiuzi,Y.,hongzheng,L.,Lei,C.,Zhiyang,C.,Xiang,P.,Sanyuan,Z.,"Reverse innovative design-an integrated product design methodology", computer aided design, elsevier,2007

Associate Professor
Sébastien Remy
Université de Technologie de Troyes, Mechanical Engineering
12 rue Marie Curie, 10010 Troyes, France
Email: sebastien.remy@utt.fr