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Procedia CIRP 38 (2015) 153 – 158
www.elsevier.com/locate/procedia

The Fourth International Conference on Through-life Engineering Services

Method for automated structuring of product data and its applications

Sebastian Adolphy[a,*], Hendrik Grosser[a], Lucas Kirsch[a], Rainer Stark[a,b]

[a]*Division of Virtual Product Creation, Fraunhofer IPK Berlin, Germany*
[b]*Chair of Industrial Information Technology, TU Berlin, Germany*

* Corresponding author. Tel.: +49 (0)30 39006-216; fax: +49 (0)30 3930246. *E-mail address:* sebastian.adolphy@ipk.fraunhofer.de

Abstract

Product structures represent the data backbone for through-life management of complex systems. Product Lifecycle Management (PLM) Systems are used to maintain product structures and track product changes. However, in maintenance, repair and overhaul (MRO) product composition often is unknown when MRO service providers are not the original manufacturers. Thus, MRO processes start with an exhaustive product diagnosis to identify elements to be maintained or replaced. Existing 3D scanning and data post processing methods have to be improved to acquire structured product data. This paper presents a method for automated derivation of product structures from 3D assembly models.

Peer-review under responsibility of the Programme Chair of the Fourth International Conference on Through-life Engineering Services.

Keywords: Product structure; graph theory; product data management; reverse engineering; 3D scanning

1. Introduction

Product data is essential for efficient through-life engineering services, since it is the basis of any systematic maintenance, repair and overhaul (MRO) planning and operation. However, life cycle based documentation of changes regarding product configuration, condition and functionality is still an unsolved problem for holistic product life cycle management approaches [1]. Consequently, MRO service providers have to diagnose characteristics individually for any specific product. Each life cycle stage modifies the product structure: Stages to distinguish are design (as-designed), production (as-produced), use (as-used), MRO (as-maintained) and recycling (as-recycled). Change notification is not shared in B2B and B2C networks due to reasons of intellectual property, quitted businesses or data conversion problems in incompatible or aging IT infrastructure. Efficient data reconstruction or retrieval strategies are needed for fast product diagnosis and documentation. These strategies comprise reverse engineering of 3D models for overhaul projects [2]. 3D models and other product data required for MRO activities can be managed in PLM-Systems. Today's PLM-Systems are not restricted to the creation of products, but can be used for spare part management, reengineering processes, asset management and many other MRO-tasks. The product structure forms the data backbone of these PLM systems. Hence structured storage of data generated within MRO activities is inevitable.

This paper deals with structuring of geometric product data coming either from a reverse engineering or a forward CAD modeling process within MRO processes. A method has been developed for visually and algorithmically assisted structuring of product models. The semiautomatic process uses a 2D-contact graph which is derived from a 3D-model by a neighborhood analysis to identify logical groups for building a structure. Data transfer of structure information is performed by a PDMXML file. Industrial benefits may be to reduce the effort of structure management divisions within the product engineering areas of large companies. Although this paper addresses especially the through-life engineering topic the solution approach is also relevant for the design stage within the product creation process.

Peer-review under responsibility of the Programme Chair of the Fourth International Conference on Through-life Engineering Services.
doi:10.1016/j.procir.2015.07.063

2. Initial situation and state of the art

Currently there is no approach for automatic identification of product structures for 3D product models without a given assembly structure available. If structured product data is required within a MRO process (as described in chapter 4), comprehensive knowledge on the respective product is needed to manually model a proper product structure [3]. In many cases this knowledge is not available, especially in cases of long-life systems and for third party service contractors.

Research on Reverse Engineering and reconstruction of mechanical products focuses on recognition of single surfaces rather than on whole assemblies and its product structures. Principles are based on basic primitives like spheres, cylinders, cuboids [4] or other features and constraints [5]. Segmentation methods are used to detect edges and surfaces [7,6]. The goal of reconstructing whole industry sites or buildings including single object information is pursued by Building Information Modeling (BIM) applications. Complete elements of the structure are virtually rebuilt and component lists can be created [8,9]. However, despite semi-automated features for reverse engineering effort is still high [12,11,10].

For the understanding of the presented method and its benefits regarding the current practice of generating structured product data in MRO processes two questions have to be answered:

1. What is the output of 3D scanning?
2. How are product structures generated?

2.1. Output of 3D scanning principles and post-processing

The result of a 3D scan is a point cloud which includes x-,y-,z-information as well as a normal direction. Standard software creates a mesh or polygon surface. Due to limitations of visibility or difficult capturing of shiny or concave surfaces the resulting mesh may be incomplete and may show artifacts. Usually manual post-processing of these meshes with suitable software features is performed. There are several data formats for polygon models such as STL, PLY, OBJ or WRL. For CAD modification a further processing step called surface reconstruction is necessary. The results are Non-Uniform Rational B-Spline (NURBS) surfaces.

Reverse engineering of assembly models consisting of single parts is done as follows: First, a 3D scan of the complete assembly is performed. Then, the physical assembly is disassembled and 3D scans have to be made of each single part. Finally, the resulting 3D polygon models are referenced to the initial 3D scan. This is possible with special reference markers that can be stickers put onto the object's surface. Creation of CAD assembly models is more elaborate. The single part's 3D polygon models have to be reverse engineered to surface models respectively CAD parts. These CAD parts are assembled in a CAD tool by visual comparison with the physical model. There is no difference or advantage to the forward engineering process. In previous research an enhanced reverse engineering process has been presented to automate reverse engineering of assembly models [2].

2.2. Generation of product structures

A given set of product parts can be classified and structured in various ways. The chosen approach differs in dependency of the intended use of the structured product data [13]. For the generation of the initial product structure in the begin of product life the two major rivaling perspectives in industrial practice are those of engineering design on the one hand and manufacturing on the other hand. Whereas designers prefer functional oriented structures as this complies with their mindset of thinking about products, manufacturing favors a structure oriented on the production process. Other stakeholders in later lifecycle phases – in particular MRO and other services – have differing requirements on product structures. This results in many cases in the use of different product structures for the same system throughout its lifecycle. Workload for creation, transformation, maintenance and linking of these product structures cumulates in a substantial share of the overall costs of product creation and service.

Setting up of product structures in PLM systems is a manual task if there is no interface to CAD system available or if 3D product models have been generated by a reverse engineering principle. Big companies have divisions for data generation or modeling, product structure management in PLM Systems and usage of data for reengineering. The structure manager has to code single part files following the company's specific naming convention. Therefore he has to set up a PLM structure template which includes main structure nodes meaning sub-assemblies and related parts. This template is custom made for a product and cannot easily be transformed to another product or a variant of a product. Then, he has to save CAD models in a proprietary file format with a specific name and ID according to the structure template. Afterwards he imports all CAD files into the PLM system and stores them as datasets. For visualization he has to create additional files such as JT files form the proprietary files either with the CAD tool or an extra tool to import and store it to the right data set. To sum up the whole process of structure managing is highly manual and error-prone because of no exiting error recognition system or functionality.

3. Method for automated structuring of product data

The developed method for automated generation of product structures is a two-step procedure:

1. Identification of spatial relations between parts
2. Hierarchical structuring of related parts.

The approaches to these steps are described in the following.

3.1. Step 1: Neighborhood analysis using contact graphs

Prior to the explanation of the applications it is important to understand the fundamentals of graphs and their characteristic in this particular case. A graph G is an abstract datatype which represents a structure. It consists of a finite set of vertices (or nodes) V and edges E. Additionally, it is possible to assign attributes η and v to edges and vertices given a node label alphabet L_v and an edge label alphabet L_e [14].

$$G = \{\{V, E, \mu, \eta\} | v, e \in \mathbb{R} \quad (1)$$
$$\eta: v \rightarrow L_v;\ \mu: e \rightarrow L_e$$

Figure 2 shows an exemplary graph representation of a car alternator. In this case vertices represent a physical part/assembly of a product while an edge represents a direct spatial contact between two parts/assemblies. The relations (edges) between the vertices are saved in an adjacency matrix or list. The advantages and disadvantages of a matrix or list representation depend on the used algorithms. GraphML offers a comfortable data format to archive and exchange the graphs.

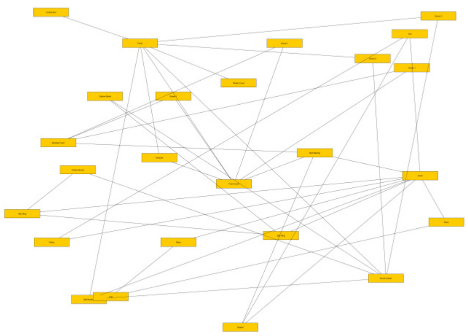

Figure 2: Example of a product graph (car alternator)

In a basic form the attributes of a vertex only consist of two entries, the vertex name and a vertex ID for intern processing. The undirected edges of the graph own no attributes; this means the only information contained is the existence of a connection between two parts.

For creating a contact graph, it is necessary to analyze the neighborhood of the parts of a product in its 3D-model. Geometric 3D-models can be represented in various formats. It is important to consider the possible input formats before deciding about a transformation method. This paper focuses in particular on tessellated surface models as input data. Prerequisite for the neighborhood analysis of the imported tessellated surface models is the complete transformation of the scanning generated point cloud into a global coordinate system. Goal of the neighborhood analysis is to identify all possible spatial contacts between the product parts. Using a brute force approach for the identification of these contacts it would be necessary to compare each triangle of the surface model. In order to reduce computing time by avoiding superfluous comparisons of triangles the method uses a three-stage neighborhood analysis. The first two stages are based on the comparison of bounding volumes (envelops). Especially the highly simplified comparison for axis aligned bounding boxes reduces the computation time significantly. The last stage consists of tri-tri Möller intersection tests of only two triangles at a time [15]. The procedure starts with assigning bounding volumes to each part of the product. If they possess an intersection there is no contact edge between these parts and the analysis can turn to other parts. If they intersect, the level of detail is increased for the analysis of this segment. Now the bounding volume intersection test is repeated on the mesh level. This means, bounding volumes are assigned to every triangle of the two considered parts and mutually tested for intersection. If each intersection test is negative there is once again no edge between these parts. If there is an intersection a detailed tri-tri Möller algorithm is applied to these two triangles for verification of the contact. This kind of collision approach is also a well-known procedure in game development.

3.2. Step 2: Cluster analysis for product structuring

In the second step of the proposed method the derived 2D graph representation is used as an input for a cluster analysis. By applying a cluster algorithm to a graph it is possible to divide it in several subgroups. In order to build a product structure with more than one level it is necessary to apply a cascading sequence of clustering steps in a top-down process (Figure 4).

The graph theory provides different algorithm for clustering. Based on the assumption that the structural groups of a product structure are well-separated modules with sparse connection between each other the Girvan-Newman algorithm is selected. This algorithm has originally been developed for identification of community structures in social and biological networks. It is based on the so called “edge betweeness” which is calculated for every edge of the created graph. A high value of edge betweeness is an indicator for connecting edges between two communities.

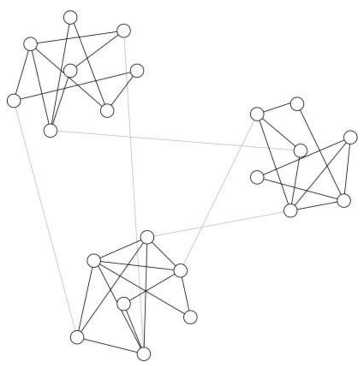

Figure 3: Schematic representation of a network with community structures (grey edges = high betweeness value) [16]

It is calculated by the sum of shortest paths between pairs of other vertices that run through the edge. The communities are formed by progressively deleting the edges with the highest betweeness value and recalculating the betweeness values. The stop mechanism can be set by a betweeness-threshold or a minimum number of communities [16].

The above described cluster analysis is resulting in a single graph only. To build a product structure with multiple levels it is indispensable to repeat the cluster analysis on every node of the future product structure. After each cluster analysis a manual check for correctness to enable potentially needed modifications is recommended.

The top down procedure of structuring the product hierarchical (Figure 4) starts with the root node of a product structure which represents the entire product with all its parts. Afterwards, those clusters are selected which require further subdivision.

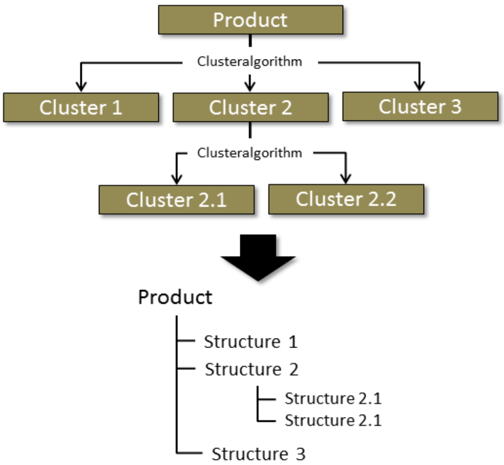

Figure 4: Top-down process for product structuring by cluster analysis

3.3. Implementation of the method

For its evaluation the above outlined method has been implemented in a software prototype, which consists of the following five functional elements:

1. STL Importer:
   The STL importer parses single STL files. For the assignment every part has to consist of an single STL file and the point cloud of each file has to be represented in a global coordinate system.
2. Neighborhood Analyzer:
   The function analyzes the imported STL files and draws a 2D-contact graph.
3. GN-Cluster function:
   The function divides the selected graphs into subgraphs.
4. Graphical User Interface (GUI):
   The GUI consists of a 3D-visualization to support the human decision process for group selection and corrective actions. It displays the actual product structure and highlights currently selected structure knots via 3D visualization. Additionally, a drag and drop feature for manual manipulation of product structures is supported.
5. PLMXML Exporter
   The module generates a PLMXML file for combined and comfortable import of the derived product structure and the STL files in a PDM system.

4. Applications of the method

This chapter describes the new principle of facilitated product structuring.

4.1. Structuring of digitized systems

Reverse engineering in MRO processes is the major use case for the developed method. The scanning of defective systems enables detection of deviations between as-used and as-design condition in the first place. If as-designed models are not available they can be created based on the digitized systems. When relevant deviations are found the digitized as-used system model can be employed in the following for the definition of repair measures or spare part production. As defective systems are rarely isolated components, structuring of the digitized system is necessary. The ability to generate structured models by scanning systems without prior disassembly is highly favorable in terms of downtime reduction [2].

Step 1 - Neighborhood analysis using contact graphs - is demonstrated by application of the method to a reverse engineered car alternator. The imported parts are shown in Figure 5.

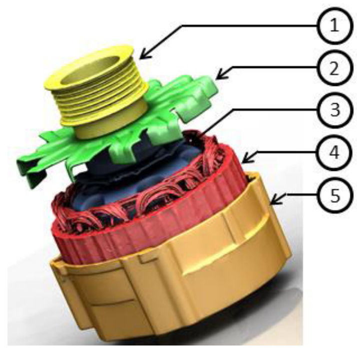

Figure 5: 3D model of a car alternator generated from 3D scan data
(1. Pulley, 2. Fan, 3. Rotor, 4. Inductor, 5. Housing)

The single parts are optically 3D scanned with a GOM Atos III®-Scanner and automatically matched in a scan of the assembled parts by a best-fit algorithm in Geomagic Studio®. Afterwards, the referenced parts are saved in single STL files. The prepared STL files are imported and analyzed in the software prototype. The resulting adjacency matrix is shown in Figure 6.

	FAN	Pulley	Housing	Rotor	Inductor
FAN		connected		connected	
Pulley	connected			connected	
Housing					connected
Rotor	connected	connected			connected
Inductor			connected	connected	

Figure 6: Adjacency matrix of the imported files

The neighborhood has been analyzed correctly, except the connection between rotor and inductor. The falsely identified connection between these parts resulted from a poor alignment in the 3D model (Figure 7). The gap between these parts is very small which implies high demands on the referencing process.

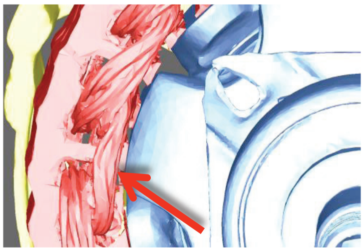

Figure 7: Connection between rotor and inductor in the 3D model of the alternator

4.2. Structuring of 3D CAD models

Step 2 of the method, the structure generation by clustering, can best be demonstrated by the analysis of an original 3D model, as long as the neighborhood analysis is not affected negatively by scanning imprecision or artifacts.

Structuring of given 3D CAD models is necessary in MRO when a system model - generated by 3D scanning (as described in the previous use case) – has to be compared with the related as-designed model. A software supported comparative analysis of product models requires identical product structures. By application of the proposed method identical structures can be generated for both the original and the scanned model.

Demonstrated by the as-designed model of the before mentioned alternator - imported as 25 separate tessellated STL files - the part's neighborhoods could be detected without errors in the first step. When applied to the root node in the second step, the clustering algorithm automatically allocated the first level of the product structure in three different groups. The first and second cluster is characterized by the static parts grouped respectively to the two-parted-housing. The third group is characterized by the rotating parts of the alternator. To illustrate the generation of a product structure with more than one structure level the authors opted for a subdivision of group 3 into two parts. The algorithm separated the coil and its holders from the rest of the group and the whole structure was created without manual post-editing.

The created product structure (Figure 8) is saved in a PLMXML file while the imported STL files are automatically linked. Then it is possible to import the structure and its parts in a single import step in PLM systems.

Figure 8: Structured as-designed model of car alternator

4.3. Restructuring of product data

In the aforementioned application the structuring of given 3D CAD models has been described, in case of the need for comparable as-designed and as-used models. A special variant of this use case is given if the original model comes with a given product structure in a PLM system. Unless the given structure has been generated analog to the clustering algorithm in the first place a restructuring of the product is prerequisite for the model-based failure detection in MRO processes.

This use case is demonstrated by the clustering of a fuel tank assembly. The fuel tank model and its product structure are provided by an automotive manufacturer. The model consists of 37 parts which should be clustered in three groups (Figure 9).

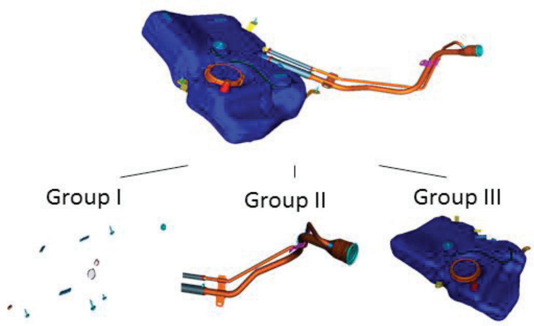

Figure 9: Target groups for clustering of a fuel tank

Under the assumption that the algorithm is not able to identify the structural unconnected group I, the parts of this group were excluded from the analysis. Thus, only group II and group III had to be found. The algorithm created three clusters.

The parts of group II are clustered correctly, except for one part, which is assigned to group III. Considering group III, 12 out of 14 parts are clustered correctly. One missing part is assigned to group II and the second is assumed to be a separate cluster with just a single part in it.

5. Summary and Outlook

The basic import function and neighborhood analysis works error-free, as long as the import model is error-free as well. Thus, if the 3D assembly model is derived from a reverse engineering in a MRO process the latter has to be very precise which means no incorrect touching parts. Details of the tests run on the software prototype related to the three described use cases have been described in [17].

The top-down process is a possible way to create a multilevel product structure. This process relies on a manual selection for further clustering. Thus, the user needs a minimum level of knowledge about the product and how to structure it. The 3D visualization, especially the highlighting of structural groups, is an important feature for support of human interaction. In addition manual modification allows fast drag and drop of datasets.

The developed method is not limited to the presented applications within MRO processes. An interesting future area of application could be a comparison of products by means of pattern matching between two contact graphs. This could enable fast query search of structural related products in big data stocks.

Another application could be a metadata independent product variant analysis by comparison of product structures. This might help to detect errors of structure management divisions.

A third field of application might be facilitation of data exchange between incompatible software systems or structure conventions of either different companies or of company's divisions. This could be achieved by provision of a platform independent template structure in the PLMXML format that supports translation of one specific product structure to the structure convention of the other software system.

Acknowledgement

This research was supported by the senate administration of Berlin (Senatsverwaltung für Bildung, Wissenschaft und Forschung) and funded by the European Union with EFRE means.

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