Reverse Engineering in Product Manufacturing

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Abstract: ***Reverse engineering plays vital role in the branch of the mechanical design and manufacturing based industry. This technique has been widely recognized as an important technique in the product design cycle. In regular computerized manufacturing environment, the operation order usually starts from the product design and ends with machine operation to convert raw material into final product. It is often essential to reproduce a CAD model of existing part using any digitization techniques, when original drawings or documentation are not available and used for analysis and modifications are required to construct a improved product design. In reverse engineering approach the important steps involved, are characterizations of geometric models and related surface representations, segmentation and surface fitting of simple and free-form shapes, and creating accurate CAD models. The chapter presents review on reverse engineering methodology and its application areas related to product design development. The product re-design and research with reverse engineering will largely reduced the production period and costs in product manufacturing industries.***

Keywords: reverse engineering, rapid prototyping, point cloud/STL data, software and Hardware, CAD/CAM/CAE

1. Introduction

The world has witnessed three digital convergences during the past three decades. Each time new technologies break down the barrier between physical and digital forms, new products and new markets has been created. The 1970s ushered in digitized sound using signal processing (1D), which made analog and digital conversion part of a common language in the telecom industry. The 1980s brought digitized fonts and pictures using image processing (2D). The convenience of switching between electronic and paper documents changed the publishing industry and the way to store and share information. The third convergence, beginning in the 1990s, focus on digitizing the physical world using geometry processing (3D). The convergence of physical and digital worlds enabled by reverse and forward engineering technologies should fundamentally change the way products are designed, manufactured, and marketed. By create a digital duplicate of world as easily as taking a digital picture, the biggest breakthrough of the twenty-first century will be in manufacturing industry.

Reverse engineering can be applied to re-create either the high-value commercial parts for business profits or the valueless legacy parts for historical restoration. To accomplish this task, the engineer needs an understanding of the functionality of the original part and the skills to replicate its characteristic details. In the fields of mechanical engineering and industrial manufacturing, reverse engineering refers to the method of creating engineering design and documentation data from existing parts and their assemblies. While in conventional engineering process, transforms engineering concepts and models into real parts, in the reverse engineering approach real parts are transformed into engineering models and concepts. Reverse engineering has a very common a broad range area such as mechanical engineering, software engineering, animation/entertainment industry, microchips, chemicals, electronics, pharmaceutical products etc. Focusing on the mechanical engineering domain, through the application of reverse engineering techniques an existing part is recreated by acquiring its' surface or geometrical features data using contact or non contact digitizing or measuring devices. By using reverse engineering, creation of product takes advantage of the extensive use of CAD/CAM/CAE systems. And apparently provides enormous gains in improving in quality, materials properties, efficiency of re-design, manufacture and analysis. Therefore, reverse engineering is going with substantial business benefits in shortening the product development cycle.

Reverse engineering has been used to produce many mechanical parts, such as seals, O-rings, bolts and nuts, gaskets, and engine parts, and is widely used in many industries (Tut, 2010). The Society of Manufacturing Engineers (SME) states that the practice of reverse engineering "starting with a finished product or process and working backward in logical fashion to discover the underlying new technology" (Francis, 1988). Manufacturers all over the world have practiced reverse engineering in their product development. The new analytical technologies, such as three-dimensional (3D) laser scanning and high-resolution microscopy, have made reverse engineering easier, but there is still much more to be learned.

The part produced through reverse engineering should be in compliance with the requirements contained in applicable program criteria. To achieve a successful reverse engineering process requires. Though it roots back to ancient times in history, the recent advancement in reverse engineering has elevated this technology to one of the primary methodologies utilized in many industries, including aerospace, automotive, consumer electronics, medical device, sports equipment, toy, and jewellery. It is also applied in forensic science and accident investigations.

2. History

Reverse engineering was often used during the Second World War and the Cold War. It is often used by military in order to copy other nation's technology, devices or information, or parts of which, have been obtained by regular troops in the fields or by intelligence operations. In the last few years, increased computational power, more computer memory, and high-speed contact or non-contact scanning devices, discrete geometry has gained increasing importance in automotive design, manufacturing, and quality assurance. In recent year, the impact of reverse engineering

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in manufacturing industry is increase day per day and it also plays a significant role in promoting industrial evolution by just introducing the expensive products and stimulating additional competition. However, the average life cycle of modern inventions is much shorter. To accommodate this rapid rate of reinvention of modern machinery and instruments, reverse engineering provides a high-tech tool to speed up the reinvention process for future industrial evolution. Reverse engineering plays a significant role in the aviation industry primarily because of the following reasons: maturity of the industry, advancement of modern technologies, and market demands. From the dawn of the aviation industry in the early 1900s to its hardware maturity with the development of jet aircraft in the 1950s, the aviation industry revolutionized the modes of transportation in about 50 years.

3. Reverse Engineering

Reverse engineering is the process of obtaining a geometric CAD model from measurements acquired by contact or non-contact scanning technique of an existing physical model (Liang & Grier, 2000).The characterizes typical procedure of reverse engineering is showing in figure 1.

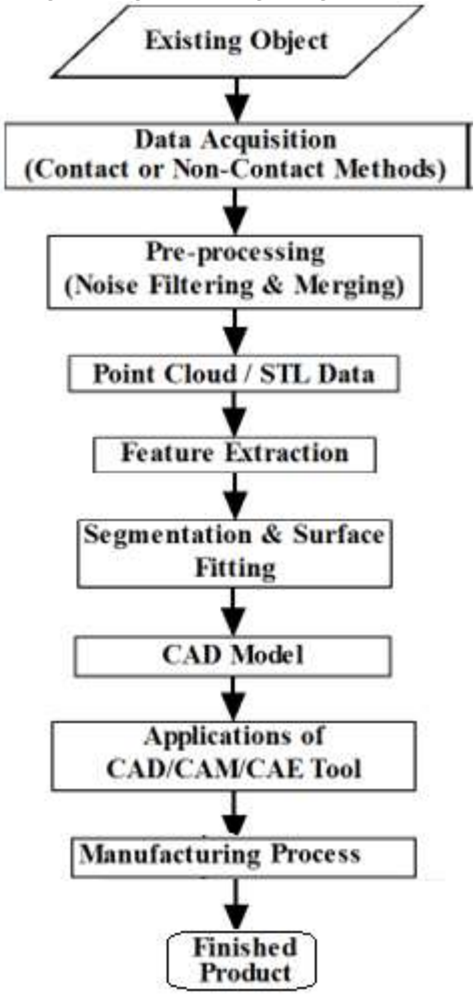

Figure 1: Basic flow of reverse engineering

It consists of following steps: data acquisition, pre-processing (noise filtering and merging), triangulation, feature extraction, segmentation and surface fitting and application of CAD/CAM/CAE tools.

4. Computer Aided Reverse Engineering

Reverse Engineering originally emerged as the answer to provide spares for replacing broken or worn out parts for which no technical data was available. This can be the case if the part was originally imported (without drawings) or the drawings being misplaced or lost. Reengineering or reverse engineering such parts can be a less expensive option compared to re-importing, not only for immediate replacement, but also to create additional spares to maintain the product over a longer period. Computer-based surface models are indispensable in several fields of science and engineering. For example, the design and manufacturing of vehicles, such as cars and aircrafts, would not be possible without sophisticated CAD and simulation tools predicting the behaviour of the product. The point cloud acquisition generally is performed by stationary scanning devices, like laser-range or computer-tomography scanners. After taking multiple scans from various sides or by rotating the object, the sampled points are combined into a single point cloud, from which the surface needs to be reconstructed. The resulting adaptive reconstruction method is based upon the repetitive application of the following steps:

- Starting from an initial bounding point enclosing the original point cloud the hierarchical space partitioning creates a point set by recursively subdividing each individual point into sub-point
- The resulting mesh is obtained by subdividing the coarser mesh and adapting its topology at locations where point have been removed
- The final data mapping locally constrains the mesh toward the point cloud. All vertices are projected onto local tangent planes defined by the individual points.

Reverse Engineering has been defined as a process for obtaining the technical data of a critical spare component. Computer-aided reverse engineering relies on the use of computer-aided tools for obtaining the part geometry, identifying its material, improving the design, tooling fabrication, manufacturing planning and physical realization. A solid model of the part is backbone for computer-aided reverse engineering. The model data can be exported or imported into CAD/CAE/CAM systems using standard formats such as IGES, STL, VDA and STEP.

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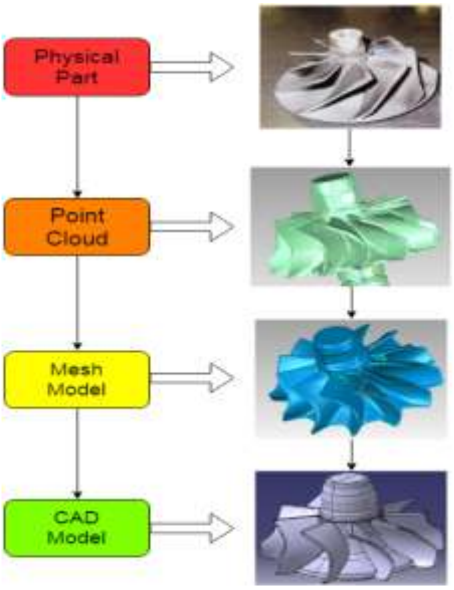

Figure 2: Physical-to-digital process

5. Basic Steps in Reverse Engineering

Although several rapid prototyping techniques exist, all employ the same basic five-step process]. The steps are:

1) Create a CAD model of the design
2) Convert the CAD model to STL format
3) Slice the STL file into thin cross-sectional layers
4) Construct the model one layer atop another

Clean and Finish the Model

The basic methodology for all current rapid prototyping techniques can be summarized as follows:

A CAD model is constructed, and then converted to STL format. The resolution can be set to minimize stair stepping. The RP machine processes the STL file by creating sliced layers of the model. The first layer of the physical model is created. The model is then lowered by the thickness of the next layer, and the process is repeated until completion of the model.

5.1 CAD Model Creation

First, the object to be built is modeled using a Computer-Aided Design (CAD) software package. Solid modelers, such as Pro/ENGINEER, tend to represent 3-D objects more accurately than wire-frame modelers such as AutoCAD, and will therefore yield better results. The designer can use a pre-existing CAD file or may wish to create one expressly for prototyping purposes. This process is identical for all of the RP build techniques.

5.2 Conversion to STL Format:

The various CAD packages use a number of different algorithms to represent solid objects. To establish consistency, the STL (stereo-lithography, the first RP technique) format has been adopted as the standard of the rapid prototyping industry. The second step, therefore, is to convert the CAD file into STL format. STL files use planar elements, they cannot represent curved surfaces exactly.

Increasing the number of triangles improves the approximation, but at the cost of bigger files size. Large, complicated files require more time to preprocess and build, so the designer must balance accuracy with manageability to produce a useful STL file. Since the stl format is universal, this process is identical for all of the RP build techniques.

5.3Slicing of the 3D model into many layers:

In the third step, a pre-processing program prepares the STL file to be built. Several programs are available, and most allow the user to adjust the size, location and orientation of the model. The pre-processing software slices the STL model into a number of layers from 0.01 mm to 0.7 mm thick, depending on the build technique. The program may also generate an auxiliary structure to support the model during the build. Supports are useful for delicate features such as overhangs, internal cavities, and thin-walled sections. Each PR machine manufacturer supplies their own proprietary preprocessing software.

5.4 Layer by Layer Construction:

The fourth step is the actual construction of the part. Using one of several techniques RP machines build one layer at a time from polymers, paper, or powdered metal. Most machines are fairly autonomous, needing little humanintervention.

5.5 Clean and Finish:

The final step is post-processing. This involves removing the prototype from the machine and detaching any supports. Some photosensitive materials need to be fully cured before use. Prototypes may also require minor cleaning and surface treatment. Sanding, sealing, and or painting the model will improve its appearance and durability.

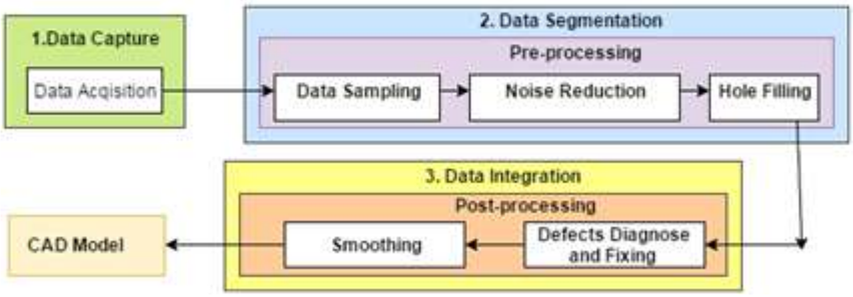

Figure 3: Detailed steps in Reverse engineering

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6. Software and Hardware used in Reverse Engineering

Reverse engineering is a process of analyzing an object or existing system (hardware-software) to identify its components and their interrelationships and investigate how it works to redesign or produce a copy without having the design from which it was originally produced. Reverse engineering hardware is used for data acquisition, which for 3D modeling, is the collection of geometric data that represents a physical object.

Reverse engineering software is employed to transform the Reverse engineering data produced by Reverse engineering hardware into 3D geometric models. The final outputs of reverse engineering data processing can be polygons model (mesh model) or Non Uniform Rational BSplines model. Normally a polygon model will be in sterolithography (STL) format, used generally for Rapid Prototyping applications, where as NURBS surfaces are frequently used in CAD/CAM/CAE applications.

6.1Reverse engineering-Hardware classification

3D scanning technology made tremendous progress in the recent past precisely, availability of non-contact optical surface digitizers. These scanners or digitizers are more portable, affordable; and yet capture points quickly and more accurately. A hand held laser scanner can capture thousands of points per second with a level of accuracy around 40 microns, and can cost as low as fifty thousand dollars, such as ZScanner 800 (ZCorp). Hence such scanners became largely accepted and widely used in industry and academia for a broad range of engineering assignments. Therefore, demand is increasing exponentially for geometric modeling technologies and software tools that can efficiently process large amount of data points and convert them into useful forms, such as NURB (non-uniform rational Bspline) surfaces. Fig 4 shows categorization of scanners based on data acquisition techniques.

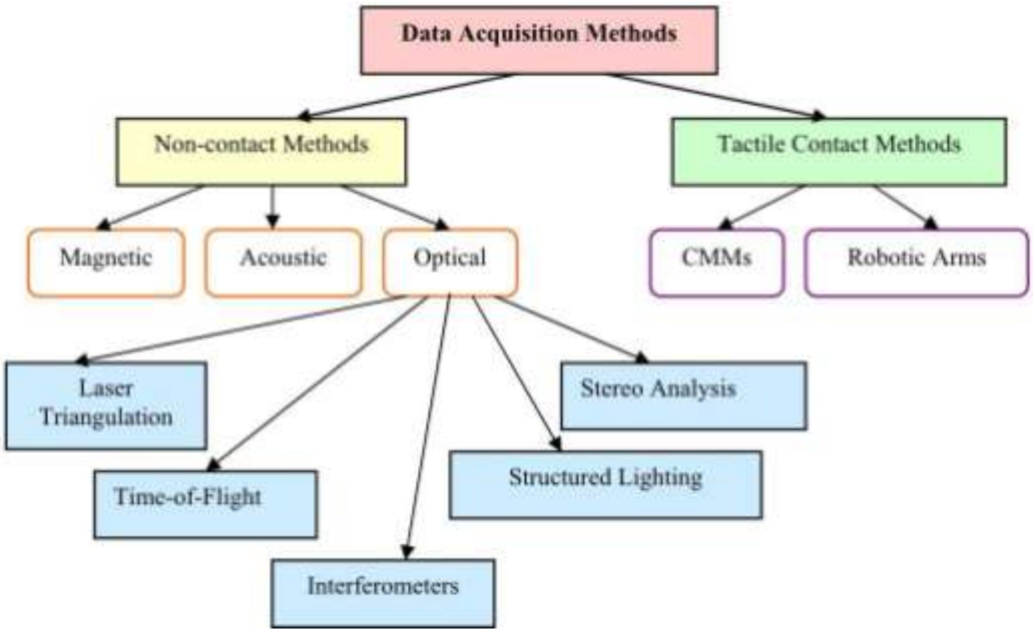

Figure 4: Classification of data acquisition methods

6.2 Contact methods

Contact methods are sensing devices with mechanical arms, coordinate measurement machines (CMM) (Fig.5), and computer numerical control (CNC) machines, to digitize a surface. In contact methods, there are two types of data collection technique, namely Point to point sensing with touch trigger probe and Analog sensing using scanning probe.

In point to point sensing technique, a touch trigger probe installed on a CMM or on an articulated mechanical arm is used to gather the coordinate points of a surface. Multiple degree of freedom movement to collect measurement points is possible through a manual, articulated mechanical arm with a touch trigger probe. Programming to follow planned paths along a surface can be done for a CMM with a touch trigger probe. A CMM generally provides more precise measurement data than the articulated arm. CMM cannot be used to digitize complex surfaces in the same way as an articulated arm due to the lack of number of degrees of freedom.

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Figure 5: TesaMicrohite 3D DCC Coordinate Measuring Machine

In analogue sensing, a scanning probe is used that is installed on a CMM or CNC machine. The scanning probe provides a continuous deflection outputs that can be combined with the machine position to derive the location of the surfaces. When scanning, the probe stylus tip contacts the feature and then moves continuously along the surface, gathering data as it moves. Therefore, throughout the measurement, it is necessary to keep the deflection of the probe stylus within the measurement range of the probe. The scanning speed in an analogue sensing is up three times faster than in point-to-point sensing. The advantage of contact methods are high accuracy, low cost and insensitivity to color or transparency. The disadvantages of contact methods are slow in data collection and distortion of soft objects by probe contact.

6.3 Non-contact methods

In non-contact methods energy sources (light, sound, or magnetic field) are projected on to the object to capture 2D cross sectional images and point clouds or reflected is seen. Triangulation, time of flight, wave interference that represent the geometry of the object and therefore the energy either transmitted information, and image processing algorithms are used to calculate the geometric data for an object. During data acquisition there is no contact between reverse engineering hardware and an object. (Fig.6).

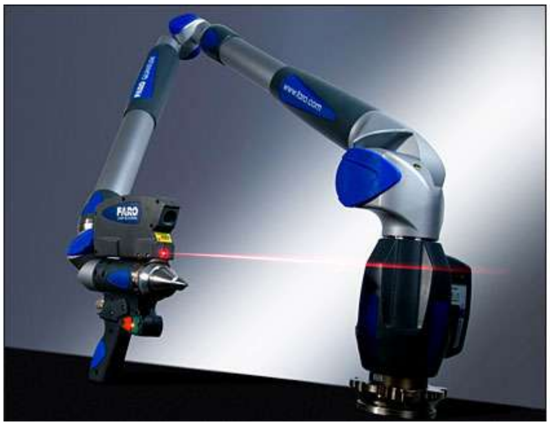

Figure 6: Faro articulated laser scanner

There are different ways to classify reverse engineering hardware that uses non-contact reverse engineering methods for data acquisition.

Table 1.1: Non-contact methods-typical commercial RE hardware

S.no	Company	Technology	Main applications
1	Cyberware	Laser triangulation	Common RE and quality inspection, Animation, fashion design, sculpturing, anthropometry, medical modeling, product development and design
2	Konica Minolta		
3	Metris		
4	Callidus precision systems		
5	Steinbichleroptotechnik		
6	Riegl	Time of flight	Topography and architectural
7	Callidus precision systems		
8	Surphaser		
9	Steinbichleroptotechnik	Structured light	Common RE and inspection
10	Genex		
11	Inspeck	Interferometry	Common RE and quality Inspection
12	Optimet		
13	Aracor	Transmission	Internal viewing, common RE and inspection
14	Micro photonics inc		

These classifications are based on sensor technologies or data acquisition techniques employed. The advantage of non-contact methods are no physical contact, fast digitization, ability to detect color and good accuracy for common applications. Table 1.1 presents some typical commercial reverse engineering hardware using non-contact methods for data acquisition.

6.4 Reverse engineering-Software classification

The complete requirements of Reverse engineering data processing and geometric modeling cannot be met by any single reverse engineering software. Reverse engineering software selection depends on the specific requirements of Reverse engineering projects.

Reverse engineering software can be divided into the following groups based on the applications: Data registration, Data manipulation, polygon manipulation,

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polygon and NURBS surface creation, CAD solid modeling, 3D inspection and NURBS surfaces and solid modeling. Table 1.2 presents these Reverse engineering software groups with representive commercial Packages.

Table1.2: Reverse engineering software classification based on application

S.no	Application	Main functions	Software
1	Data registration and Manipulation	Data acquisition, processing of basic data and Data conversion	Geomagic, Metris Scan, Cyberware, and
2	Polygon and construction of NURBS surface.	Data processing tools for working with point clouds and polygon processing	Rapidform,Geomagic, Polyworks, ParafarmCreo-REX and VRMesh
3	3D Inspection	3D inspection, creation of error map and analysis, inspection report and documentation.	Polyworks Inspector, Geomagic Control, Cloud compare and Metris Focus Inspection.
4	NURBS surfaces and CAD solid modeling	Provides NURBS modeling and editing tools.	Creo, UG, Catia, Rhino, AutoDesk Inventor and Solid works

Auto surfacing technology that automatically converts point clouds into NURB surface models was developed and implemented in commercial tools, such as Geomagic (Geomagic), Rapidform(INUS Technology, Inc.), Poly Works (InnovMetric), SolidWorks /Scan to3D (SolidWorks, Inc.), among several others in reverse engineering. Excellent accuracy, coupled with less effort and time consumption can be achieved by employing these tools to create NURB surface models. The NURB surface models are provided with geometric information to support certain types of engineering assignments in maintenance and repair industry, such as part inspection and fixture calibration. 3D modeling for bio engineering and medical applications, and automotive industry and aerospace design are supported by these surface models. NURB surface models which convert from point clouds have made remarkable contributions to broad range of engineering applications. As these models contain only surface patches without the additional semantics and topology inherent in feature-based parametric representation, they are not appropriate for design changes, feature-based NC toolpath generations, and technical data package preparation.

7. Applications of Reverse Engineering

Reverse engineering is a multidisciplinary approach and virtually can be applied to industrial field universally. The prime applications of reverse engineering are either to re-create a copy of part of the original part or retrace the events of what happened. It is widely used in software and information technology industries, from software code development to Internet network security. Thousands of parts are reinvented every year using reverse engineering to satisfy the aftermarket demands that are worth billions of dollars. The invention of digital technology has fundamentally revolutionized it. Compared to the aviation and automobile industries, the applications of digitalized reverse engineering in the life science and medical device industries have faced more challenges and advanced at a more moderate pace. However, some reverse engineering applications as follows:

- In Mechanical Industry
- In Aerospace and Ship Hull Craft
- Software Industry
- In Medical Life Science

8. Conclusion

The fundamental principles and basic limitations of reverse engineering are similar in most industries. The general practice of reverse engineering, such as data collection, detailed analysis at a micro scale, modeling, prototyping, performance evaluation, and regulation compliance, are the same in principle for all industries. The success of this endeavor is usually subject to the general limitations of modern technologies. However, the specific methodologies used in different fields can be vastly different.

The engineering design supported by CAD/CAE/CAM techniques allows optimizing the product manufacturing with assistance of CNC machine, in management for rapid product development and rapid set-up production in advance to full file the customer demand of time. For some product development processes reverse engineering (RE) allows to generate surface models by three-dimensionaland manufacture different parts (for cars, for household appliances) and tools (moulds, dies, press tools) in a short development period. As a result application of reverse engineering will gain speed for product realization system and largely decreases the manufacturing cost.

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