REVERSE ENGINEERING OF PHYSICAL OBJECTS – TEACHING MANUAL

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INTRODUCTION

The product design process, made to create new products, is a very broad concept that begins with the generation and development of new ideas and leads to the manufacturing of new products.

In the industry, the process of managing the lifecycle of a new product from inception, through engineering design and manufacturing, is called the product lifecycle management (PLM). Reverse engineering stands among all engineering processes involved in the PLM.

The Reverse engineering process has been used for many centuries. The Romans were probably the first to use this method as described by Polybius, the greatest Greek historian of his time. Polybius reported in his work *The Histories* (covers the period of 264–146 BC) how the Roman army replicated the standardization methods developed by the Carthaginians, using an existing model of Phoenician bireme ship. In just 60 days, the Romans took control of the Mediterranean Sea; managing to build a fleet of approximately one hundred ships designed on an improved version of the captured Phoenician ship.[1] This story shows how reverse engineering is useful. It is possible to recreate and improve an object or even to create an enhanced version by taking and extracting its information.

Although the reverse engineering process has been used and has been highly appreciated in the military industry of weapon manufacturing over the years, it is now proven to be very useful in different domains. In the current era of modern computers, CAD (Computer aided-design), CAM (Computer aided-manufacturing) or CAE (Computer aided-engineering) software and 3D measurement technologies, reverse engineering is used in a wide range of industries and applications.

This teaching manual introduces to the concept: reverse engineering of physical objects. It provides technical aspects of reverse engineering, such as definitions, introductions of different types of 3D scanners and their applications. It also provides the practice of reverse engineering

[1] O'CONNELL, Robert L., *Of Arms and Men: A History of War,Weapons and Agressions*, Oxford University Press, New York, 1989, p. 77.

ranging from the complete progression of data acquisition procedure to the post-treatment processing step.

1. REVERSE ENGINEERING: THE THEORY

1.1. WHAT IS REVERSE ENGINEERING?

Reverse engineering is the process that identifies an object, a device, or a system technological properties by performing a comprehensive analysis of its structure, functions and operations. In mechanical engineering, this process aims to create a virtual 3D model from an existing physical object to duplicate or to enhance it.

They are many reasons to use reverse engineering of physical objects. For example, the reverse engineering process will be used if the original design is not supported by sufficient or adequate documentation or if the original CAD model is not appropriate to support modifications and/or standard production methods. In some cases, original manufacturer no longer exists nor manufactures a product, but some requirements remain for that product. Reverse engineering would then help. In the case of worn or damaged components, for which no source of supply is available, reverse engineering building features would also to analyze competitors' products features, for performance improvement and/or product features, for lack of additional parts (spare parts) or to update obsolete materials or antiquated manufacturing process.

In order to create a 3D model of the object, the object must be measured using 3D scanning technologies (CMM, laser scanners, structured light digitizers…). Once the scanning operation is done, it is possible to rebuild the 3D model using 3D CAD, CAM, CAE or other software.

1.2. WHAT IS 3D SCANNING TECHNOLOGY?

The 3D scanning technology is the application of scientific knowledge for analyzing an object (or environment) by collecting data on its shape and, sometimes, on its appearance (color, texture) to build a 3D digital model. The device used to perform this kind of analysis is a 3D scanner.

1.3.WHAT ARE 3D SCANNERS?

3D scanners devices are very similar to cameras: they have a conical visual field and can collect information on visible surfaces. A detail makes them different: the camera collects color and surface information within its field of view (creating images) while the 3D scanner uses the images acquired to extract 3D data (collecting information on the distance and the surface within its field of view). It generally creates a geometric point cloud of the object surface. The image produced by the 3D scanner indicates, for each point, the distance to the surface. This provides the three-dimensional position for each point of the surface.

1.4.3D SCANNERS: DIFFERENT TYPES FOR DIFFERENT USE

There are many types of equipment used for measuring 3D objects. 3D scanners, dedicated for digital form acquisition, can be classified in two types of equipment: contact and non-contact 3D scanners. However, non-contact 3D scanners are also divided into two categories: passive and active.

There are a broad variety of technologies for digital acquisition of 3D object shapes. Each device has its own specifications and works differently. The following section describes each technology and will help you understand them.

1.4.1. *CONTACT*

Contact 3D scanners explore (probe) physical objects while in contact with, or holding on to, a precision plane surface, ground and polished to a specific maximum of surface roughness. When the object to be scanned is not flat or cannot be stabilized on a plane surface, it has to be supported and held in place using a fixture.

The scanner mechanism may either be a carriage system with fixed arms tightly clasped in perpendicular with each axis sliding along a track, or an articulated rigid arm provided with high precision angular sensors (Figure 1**: Articulated probing arm equipped with a ruby touch probe.**).

Source: www.hexagonmetrology.com

Figure 1: Articulated probing arm equipped with a ruby touch probe.

Resolution is one of the mesh file main properties, defining the level of details visible on scan data. It can be compared to screen resolution, which is defined by the amount of pixels. A combination of both methods can be used, such as an articulated arm suspended from a moving carriage, for mapping large objects with interior cavities or overlapping surfaces.

A CMM (Coordinate measuring machine) is an example of contact measurement system (Figure 2). It is mostly used in manufacturing and can be very precise. The disadvantage of CMMs is that they require contact with the object being scanned. Scanning the object might modify or damage it, and it is very significant when scanning delicate or valuable objects such as historical artifacts. The other disadvantage of CMMs is that they are relatively slow compared to other scanning methods. The arm on which the probe is mounted on can move very slowly, and the fastest CMMs can only run at a few hundred hertz. In contrast, optical systems such as laser scanners can run from 10 to 500 kHz.

Contact measurements systems are also highly sensitive to environment changes (vibrations, part displacement, temperature variations). In order for them to perform as indicated, these machines need to be isolated from these changes (installed on an independent concrete slab or used in a metrology lab).

Figure 2: CMM (coordinate measuring machine) with rigid perpendicular arms.

1.4.2. NON-CONTACT PASSIVE

Passive scanners do not emit any kind of radiation; they rely on detecting reflected ambient radiation. Most of these type of scanners detect visible light as it is found in the ambient radiation. Other types of infrared radiation are also used. In most cases, passive methods are generally inexpensive because they do not require particular equipment except for digital cameras. They provide low accuracy.

1.4.3. *NON-CONTACT ACTIVE*

In order to probe and object or environment, active scanners emit some kinds of radiation (X-ray, ultrasound) or light and detect the reflection or radiation passing through object. The light or radiation emitted by the scanner is reflected by the object scanned and sends back the information to the scanner, recording the surface distance. However, this type of scanners has limitations: it has difficulty scanning reflective or transparent objects.

1.4.3.1. TIME-OF-FLIGHT

The time-of-flight 3D laser scanner (Figure 3) uses a laser light to probe the subject. This type of scanner, equipped with a time-of-flight laser rangefinder, finds the distance of a surface by timing the round-trip time of a pulse of light. Moreover, the laser emits a pulse of light and the amount of time is measured before the detector sees the reflected light.

Since the speed of *light c* is known, the round-trip time determines distance travelled by the light, which is twice the distance between the scanner and the surface. If *t* is the round-trip time, then distance is equal to $c \cdot t/2$. The accuracy of a time-of-flight 3D laser scanner depends on how precisely the *t time* can be measured: 3.3 picoseconds is approximately the time taken for light to travel 1 millimeter.

The laser rangefinder only detects the distance of one point in its direction of view. The device scans its entire field of view, one point at a time, only by changing the range finder's direction of view to scan different points. The direction view of the laser rangefinder can be changed either by rotating the rangefinder itself, or by using a system of rotating mirrors. This method is commonly used because mirrors are much lighter and can thus be rotated faster with a higher level of accuracy.

The typical time-of-flight 3D laser scanners can measure the distance of 10,000~100,000 points every second.

Figure 3: Lidar (light detection and ranging) 3D scanner used to scan buildings, rock formations, etc.

1.4.3.2. TRIANGULATION

Triangulation based 3D laser scanners are also active scanners. They use laser light to probe the environment. Respecting time-of-flight 3D laser scanner, the triangulation laser shines a laser on the subject and uses a camera to look for the location of the laser dot which appears at different places in the camera field of view, depending on how far away the laser strikes a surface.

This technique is called *triangulation* because the laser dot, the camera and the laser emitter form a triangle (Figure 4). Three pieces of information determine the triangle shape and size. First, the length of one of the triangle sides the distance between the camera and the laser emitter is known. Second, the angle of the laser emitter corner is also known. Third, the angle of the camera corner is determined by looking at the laser dot position in the camera's field of view. In most cases a laser stripe, instead of a single laser dot, is swept across the object to speed up the acquisition process.

The National Research Council of Canada (NRC) was among the first institutes to develop the triangulation-based laser scanning technology in 1978.

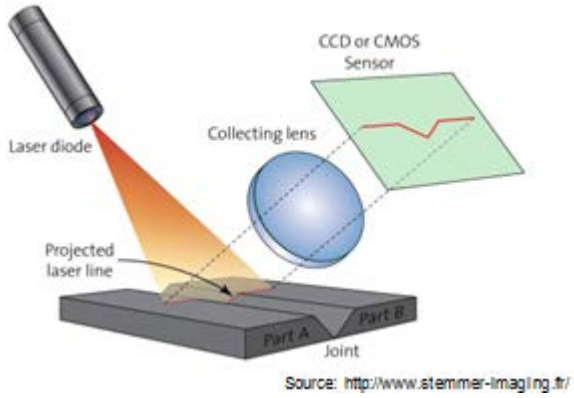


Figure 4: Principle of laser triangulation sensor.

1.4.3.3. STRUCTURED LIGHT

Structured-light 3D scanners project a light pattern on the subject. They look at the deformed pattern, which is projected on the subject using either an LCD projector or other stable light source. The camera, slightly offset from the projector pattern, looks at the shape and calculates every point's distance in the field of view. Some of those existing systems can also scan moving objects in real-time.

Structured-light 3D scanners have two main benefits: to capture speed and precision. In fact, instead of scanning one point at a time, they scan multiple points or the entire field of view at once. This means they scan the entire field of view and generate exponentially more precise profiles than laser triangulation, in a fraction of a second. This approach reduces (even eliminates) the problem of distortion from motion.

1.4.3.4. MODULATED LIGHT

The modulated light 3D scanners project a continual changing light on the subject. This creates a set of linear patterns on the object (sinusoidal pattern). A camera detects the reflected light and determines the distance the light traveled, shifting each line of the pattern.

The modulated light also allows the scanner to ignore the light from sources other than laser, so there is no interference.

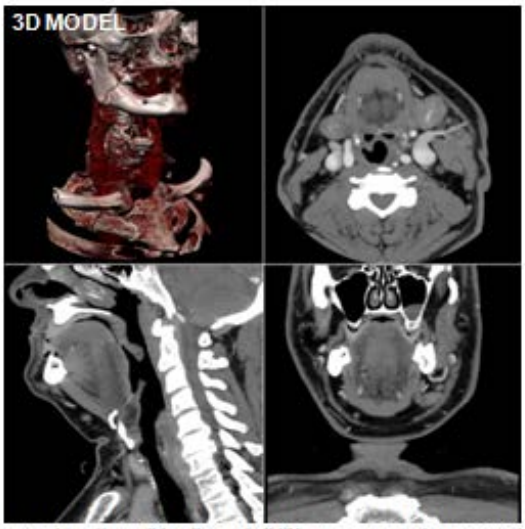
1.4.3.5. VOLUMETRIC TECHNIQUES

Industrial

Computed tomography (CT), microtomography and magnetic resonance imaging (MRI) techniques are used to acquire an object digital image including its interior, such as non-destructive material testing, reverse engineering or the study of biological and paleontological specimens. Although used in industrial domain, these techniques are more common in the medical domain.

Medical

Computed tomography (CT) is a medical imaging method, which generates a three-dimensional image of the inside of an object from a large series of two-dimensional X-ray images. Similarly, magnetic resonance imaging is another medical imaging technique that provides much greater contrast than computed tomography (CT), between the body's different soft tissues, making it especially useful in neurological (brain), musculoskeletal, cardiovascular, and oncological (cancer) imaging. These techniques produce a discrete 3D volumetric image that can be visualized, manipulated or converted to traditional 3D surface by means of isosurface extraction algorithms.[2]



Source: http://en.wikipedia.org/wiki/X-ray_computed_tomography

Figure 5: X-ray computed tomography. The 3D model (top left corner) is computed using the 2D images captures; the 3D model is reconstructed slice by slice.

[2] URL: http://en.wikipedia.org/wiki/3d_laser_scanning (consulted on February 11, 2013)

1.4.3.6. STEREO VISION

Computer stereo vision is the result obtained from the extraction of 3D information of digital images (such as CCD camera). By comparing two vantage points, 3D information can be extracted from objects relative positions in the two panels. This is a very similar process than the stereoscopic vision.

Active vs. Passive Stereo

Active stereo vision uses a light, such as laser or a structured light pattern, to simplify stereo matching challenges. The opposite of the active stereo vision is the passive stereo vision.

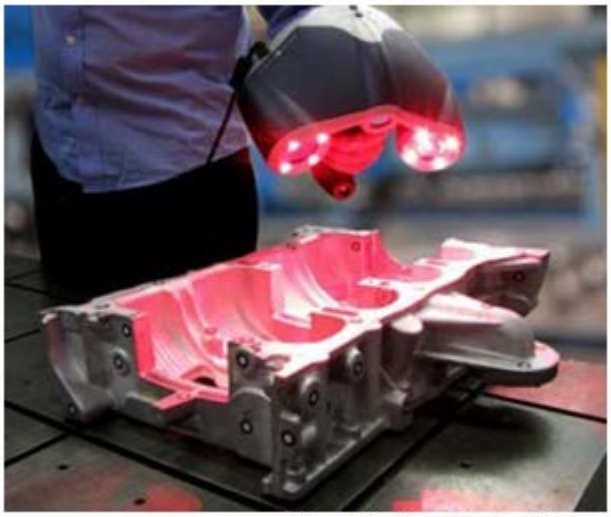
1.4.3.7. HANDHELD LASER SCANNER

The handheld laser scanners create a 3D image using the triangulation mechanism (ref. section 1.4.3.2). A laser dot (or line) is projected on the object from a handheld device (sensor) and the distance to the measurement surface. An internal coordinated system collects the data. Therefore, the scanning device position must be determined in order to collect data while the player is moving. The scanner determines the object position by using the reference features of the scanned surface (usually adhesive reflective targets). These scanners can also use the actual shape (object texture or color) using a process of external monitoring.

A laser tracker providing the sensor position often represents external tracking. An integrated camera determines the orientation of the scanner or a photogrammetric solution, using three (or more) cameras, providing a six degrees freedom for the scanner.

Both techniques use infrared light-emitting diodes attached to the scanner. Infrared light-emitting diodes are seen by the camera(s) through filters providing resilience to ambient lighting.

A computer collects the data (collected points), which is then recorded within a three-dimensional space. That can be converted into a triangulated mesh with processing and then, to the CAD model.



Source: Creaform Metrology Services

Figure 6: *HandySCAN 3D* scanner used to digitize a metal casting. The system uses stereo principle to simultaneously observe reflective markers (for positioning) and laser projection (for geometry detection).

1.4.3.8. HANDYSCAN 3D BY CREAFORM

HandySCAN 3D is a hand-held scanner manufactured by Creaform. It is a very portable and versatile self-positioning 3D scanner. It uses Creaform positioning targets to reference its position from the object to scan. This device's main characteristic is its *portability*; it refers directly to the object with targets. It can easy be carried to the object instead of bringing the object to the scanner.

Once the object and the scanner's position have been located with targets, the surface acquisition is completed through the camera. The camera sees the two laser lines, crossing each other, projected on the surface. As the surface is swept over by the laser, data is recorded based on the triangulated position. The output file format is a STL file.

1.5. LIVE SURFACE GENERATION

New 3D sensor technologies can capture 3D points at a very high rate and quickly capture very dense sets of points on the object surface (live surface generation). This large quantity of 3D points observations allows analyzing their local distribution on a section before validating their consistency with the expected error model developed at the calibration stage. High quality surface point measurements can be produced in metrology from these point observations. A smart and real-time measurement process is integrated to these steps during capture.[3]

1.6.3D SCANNING APPLICATIONS

NPD (New product development) is the process of bringing a new product to the market. There are two parallel paths involved in that process: the first one involves the idea generation, product design and detail engineering, while the second involves market research and marketing analysis.

One of the NPD concepts is product lifecycle management (PLM) in which 3D scanning plays a real key role.

[3] http://www.creaform3d.com/en/resource-center/technological-fundamentals/intelligent-measurement/documentation

1.6.1. *3D SCANNING: PART OF THE PRODUCT LIFECYCLE MANAGEMENT (PLM)*

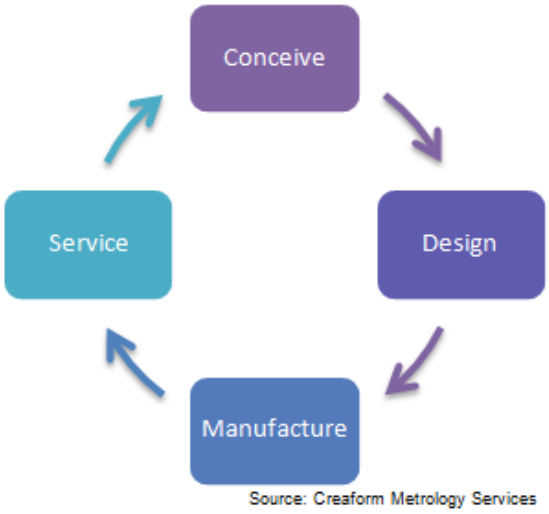


Figure 7: Simplified diagram of a typical PLM.

Conceive

The first step is to define product requirements based on the customer, the business, the market and regulatory agencies' perspective. The second step is to define the product main technical parameters. The first design work is then performed and the product aesthetics and main functional aspects are developed in parallel. Different media are used for these processes: from pencil and paper to clay models in CAID software (Computer-aided industrial design).

Design

a. Detailed Design

The first stage is product design and development. Then come the prototype and production steps. Finally, the product is launched. That can involve redesigning or improving existing products. The main tool used for the design and development is CAD software is a simple 2D drawing/drafting or a 3D parametric feature based on solid/surface modeling. CAD software

includes technologies such as hybrid modeling, reverse engineering, KBE (Knowledge-base engineering), NDT (Nondestructive testing), and the assembly model.

b. Prototyping

Prototypes are the first samples, models or versions of a product built to test the concept, process or act as a thing to replicate. It is a term used in many contexts such as semantics, electronics, software programming and product design. A prototype is primarily designed to test a new design (by analysts and/or users) and to improve a product accuracy and quality.

Formerly known as rapid prototyping, the *additive manufacturing* or *3D printing* is the process of making a three-dimensional solid object of any virtual shape from a digital model. It is used to provide specifications for a real object (instead of a theoretical system).

c. Validation, Testing and Analysis

Simulation, validation and optimization tasks are carried out using CAE (Computer-aided engineering) software either integrated in the CAD package or stand-alone. These are used to perform tasks such as stress analysis, FEA (Finite element analysis), kinematics, CFD (Computational fluid dynamics) and MES (Mechanical event simulation).

Manufacture

a. Tool Design

Once the design is validated, manufacturing needs to be foreseen, including tool design. It is based on planning how to mass-produce the project and which tools to use for the object manufacturing. At this step, the tasks include selecting production processes with the material, determining the sequence of operations, and choosing tools (such as jigs, fixtures and tooling). This task also involves testing a working prototype to make sure the object created meets qualification standards.

b. Build/Assemble/Produce

Mass production is implemented following steps of design and manufacturing processes. This is standardized products manufacturing of large quantities including (and most importantly) assembly lines.

Standardized production concepts are applied to different types of products such as fluids and particles processed in bulk (food, fuel, chemicals and mineral extracts) or discrete solid parts (i.e. fasteners) to assemble such components (e.g.: appliances and automobiles).

Mass production is a distinct field and can usually be contrasted with craft production or manufacture distributed. This production process has been widespread and is at the center of the economy since the late 19th century.

c. Quality Control

Once the manufacturing process is defined and production has started, it is time for the products to under go quality checks.

Quality checks include CAD tasks such as tool design: creation of CNC (Computer numerical control) machining instructions for the product's parts as well as tools to manufacture those parts, using integrated or separate CAM (Computer-aided manufacturing) software. This also involves using analysis tools for operations process simulation such as casting, molding, and die press forming.

Service

a. Maintenance, Repair and Operations (MRO)

Once the product is in service, it will eventually suffer from wear and tear. A continuous quality control on the product offers better visibility and can prevent heavy damage to occur. Therefore, surveillance and maintenance operations are decisive. For instance, part of an object or assembly may have to be replaced or repaired if it is damaged.

b. Dispose/Replace/Recycle

In the same way, there is an end-of-life for every product that needs to be planned. The disposal or recycling of an object has a cost and that is part of its life cycle. The dismantling of sensitive parts, such as in nuclear power plant, sometimes requires high caution and precautionary measures.

The 3D digitizing can be involved in all manufacturing industries and in every step of product lifecycle management (PLM).

1.6.2. OTHER APPLICATIONS OF 3D SCANNING

Museology, Heritage Preservation, Restoration and Digital Archiving

3D scanning technology is used for archiving, restoration or virtual museum. For example, Creaform has reproduced the monument of Francis de Gaston, knight of Lévis (**Figure 8Figure 8**). This gave the Canadian city of Lévis, Quebec, the opportunity to own a bronze statue of the historical figure after whom the city was named[4].

Source: Creaform Metrology Services

Figure 8: Reproduction of the monument of Francis de Gaston (knight of Lévis).

Another example of this application are the scans of ancient monuments realize by Ben Kacyra. Ancient monuments give us clues of the astonishing past civilizations -- but are threatened by pollution, war and neglect. Ben Kacyra invented a groundbreaking 3D scanning system (state-of-the-art technology) and is using his invention to scan and preserve the world's heritage in archival detail [5]. To view his work, go to: http://www.ted.com/talks/ben_kacyra_ancient_wonders_captured_in_3d.htm

Multimedia and Entertainment

Multimedia and entertainment industries can use 3D scanning tools in various applications, mainly to reduce modeling time, to speed up process and to make 3D graphics more realistic.

[4] URL : http://blog.creaform3d.com/2012/03/the-knight-of-levis-an-historic-figure-goes-digital/
[5] URL : http://www.ted.com/talks/ben_kacyra_ancient_wonders_captured_in_3d.html

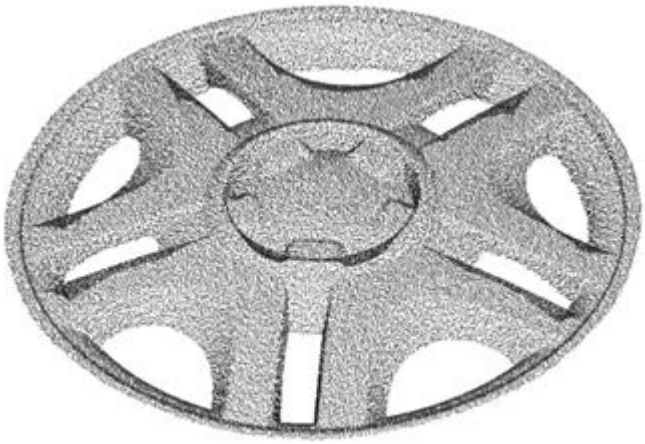
For an example of multimedia application: http://blog.creaform3d.com/2013/12/when-3d-scanning-goes-glamour-–-the-jenn-barlow's-bubble-head-project/

Virtual Reality/Augmented Reality (Serious Gaming, 3D Training Systems)

3D scanning is not only for small/medium objects. Some devices are able to capture and reconstruct an entire room or environment. The result may be reworked and transformed into a 3D virtual environment.

1.7.DEFINITIONS

1.7.1. POINT CLOUD



Source: Creaform Metrology Services

Figure 9 : Representation of point cloud shape.

In a three-dimensional coordinate system, a *point cloud* is set of data point. These points are usually defined by XYZ format and represent a set of 3D measurements. The *cloud shape* is due to the amount of measured points. A single piece of data can be measured several times from different points of view. For each of these measurements, uncertainty causes small agglomerates of points for the same data and then creates the *thickness* of the model.

Point clouds may be created by 3D scanners, which measure a large number of points of an object surface, and often output a point cloud as a data file. The point cloud represents the set of points the device has measured. As the result of 3D scanning process, point

clouds are used for many purposes including creating 3D CAD models for manufactured parts, metrology, quality inspection and for a multitude of visualization, animation, rendering and mass customization applications.

While point clouds are directly rendered and inspected, they are generally not directly usable in most 3D applications. They are usually converted to triangle mesh models (STL file) or to NURBS (Non-uniform rational basis spline) surface models through a process commonly called surface reconstruction.

1.7.2. STL/MESH FILE

Source: Creaform Metrology Services

Figure 10: Representation of STL shape.

STL (stereo-lithography) is a file format native to the stereo-lithography CAD software, widely used in 3D printing and CAD industries. This file format is supported by many other software packages.

STL files only contains the surface's geometry of a three-dimensional object without any color, texture or other common CAD model attributes. They also contain a raw unstructured triangulated surface of the unit normal and vertices (ordered by the right-hand rule) using a three-dimensional Cartesian coordinate system.

The STL format specifies both ASCII and binary representations. Moreover, binary files are more frequen since they are more compact. STL coordinates must be positive numbers. There is no scale information and units are arbitrary.

1.7.3. RESOLUTION

Resolution is one of the mesh file main properties, defining the level of visible details on scan data. It can be compared to screen resolution, which is defined by the number of pixels. The size of the triangles side on the mesh file is called the resolution (measured in millimeters). Higher resolution increases the number of triangles of a mesh file. For an equivalent object, the size of the mesh file is consequently proportional to the resolution.

Important to remember: resolution and accuracy are two different factors. The resolution only defines the level of details. A mesh can be equally accurate to another with a lower resolution. The difference is significant in highly curved areas (Figure 8).

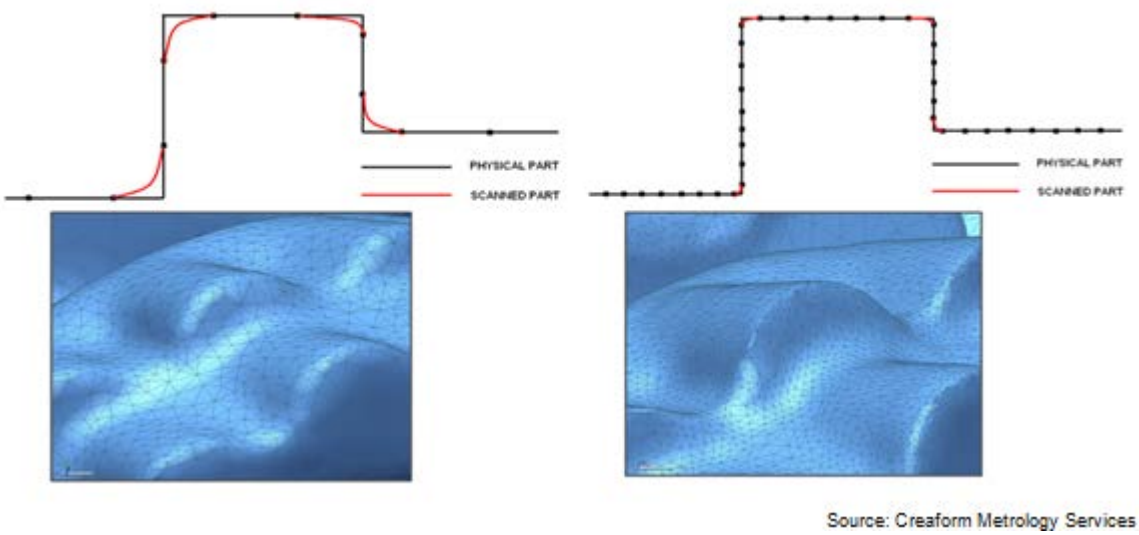


Figure 11: Difference between *Resolution* and *Accuracy*.

1.7.4. ACCURACY

In metrology, precision refers to measurement dispersion. The measurement error (the mean) can be close to zero even if the system is not very precise (but it needs a good trueness). In other words, the less scattered the measurement data is, the more precise is the equipment. A formal definition of precision is: closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions.

The word *trueness* rather gives information on the difference between the mean of measurements and the real dimension regardless dispersion. In other words, the closest the mean of measurements is to the nominal value, the more trueness the equipment has. A formal definition of trueness is: closeness of agreement between the average of an infinite number of replicate measured quantity values and reference quantity value.

Accuracy is the conformity between scan data and reality. To evaluate the accuracy of a measuring device, like a laser scanner, the data acquired with this device should be compared to the data acquired with a more accurate measurement tool (e.g.: a coordinate measuring machine (CMM)) and the measured item must be normalized.

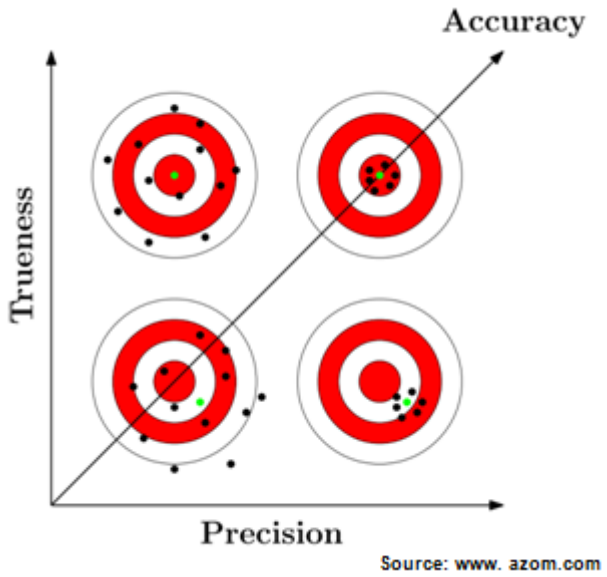


Figure 12: Representation of accuracy trueness.

1.7.5. RAW/CLEAN

A raw mesh is a file directly issued from the scanning device, before any post-treatment operation, while a file mentioned as clean, is a file that has been post-treated and ready for reverse engineering operations.

1.8. DIRECT USE OF STL MODEL

Some applications do not need a CAD file, even reverse engineering process, when the STL file is compatible and directly applies.

FEA (Finite Element Analysis)

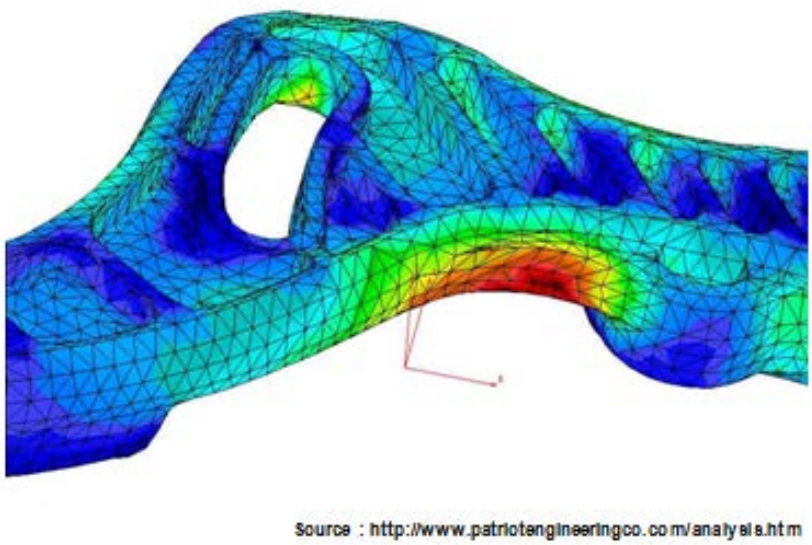


Figure 13 : Representation of finite element analysis (FEA).

In mathematics, the finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems for differential equations. It uses variation methods (the calculus of variations) to minimize an error function and produce a stable solution. Similar to the idea that connecting many tiny straight lines can approximate a larger circle, the finite element method (FEM) encompasses all the methods for connecting many simple element equations over many small subdomains, called finite elements, to approximate a more complex equation over a larger domain.

FEA, as applied in engineering, is a computational tool for performing engineering analysis. It includes the use of mesh generation techniques for dividing a complex problem into small elements, as well as the use of software program coded with FEM algorithm. In applying FEA, the complex problem is usually a physical system with the underlying physics such as the Euler-Bernoulli beam equation, the heat equation or the Navier-Stokes equations. The divided small elements of the complex problem represent different areas in the physical system.

FEA is a good choice for analyzing problems over complicated domains (as in the case of cars and oil pipelines), when the domain changes (as during a solid state reaction with a moving boundary), when the desired precision varies over the entire domain or when the solution lacks smoothness.

Rapid Prototyping

Rapid Prototyping (RP) or more generally 3D printing can be described as a group of techniques used to fabricate a scale model quickly of a part (object) or assembly using three-dimensional computer aided design (CAD) data. What is commonly considered being the first RP technique is stereolithography. Therefore, the STL file format has naturally become a standard in data transmission format for rapid prototyping industry. The mesh file can either be created from an existing CAD file or come from a 3D scanning device.[6]

Rapid Prototyping has also been referred to solid free-form manufacturing; computer automated manufacturing, and layered manufacturing. RP has obvious use as a vehicle for visualization. In addition, RP models can be used for testing or creating male models for tooling, such as molds and investment casting. In some cases, the RP part can be the final one, but typically the RP material is not strong or accurate enough. When the RP material is suitable, highly convoluted shapes (including parts nested within parts) can be produced because of the nature of RP.[7]

CNC Milling (Computer Numerical Control)

The key advantage of using an STL file format is that it communicates only the data that the NC programmer needs -- the geometry of the object. There is none of the extra information in the file to indicate the structure of the original CAD file. The process of transferring work piece

[6] http://www.efunda.com/processes/rapid_prototyping/intro.cfm
[7] Ibid

geometry from one system to another is simpler and saves work and errors since the STL file is by definition a closed, unambiguous surface. [8]

Not having access to all of the original surface data can at times prove to be a limitation, but that's certainly not a given. Indeed, if the STL file is properly constructed, it should preclude the NC programmer's need to get at the surface data in the first place. In some cases, the structure of the CAD file is proven to be a handicap, especially for small surfaces. They may need to be merged to be machined as one, when this kind of modeling operations is not necessary with STL files as the tool path only relies on the shape of the object, and not on the arrangement of component surfaces.[9]

[8] http://www.mmsonline.com/articles/machining-from-stl-files
[9] Ibid

2. REVERSE ENGINEERING: THE PRACTICE

2.1. TOOLS/DEFINITIONS

2.1.1. POINT CLOUD VS MESH FILE

Depending on the final application, both point clouds and mesh files can be of use. Each format has its own characteristics and advantages.

Source: Creaform Metrology Services

Figure 14: Point cloud vs. mesh file.

POINT CLOUD

- Can handle larger data files
- Basic measuring
- Can be used for reverse design
- Can be used for metrology/inspection
- Can be used for visualization and documentation

MESH FILE

- Can recognize features intuitively
- Distinguish front and back faces
- Can evaluate curvature
- Can measure volume
- Can accurately measure alignment between scan data
- Can be directly used in Rapid prototyping, machining…
- Can be used for reverse design
- Can be used for metrology/inspection
- Can be used for visualization and documentation
- Can be used for animation

Scan data is basically a collection of 3D points. It can be converted into a mesh by connecting adjacent points with an arrangement of triangles, which are the simplest unit of the face. The main advantage of the mesh is that it is a very visual format, offering a good visualization of the shape of the object.

Point clouds can contain more information, as files are lighter for equivalent data. The visualization is not as great as with mesh, but can be done for bigger objects. For instance with long range scan, the visualization is easier with point cloud. An STL file would take a very long time to be generated, without any guarantee of quality.

2.1.2. REVERSE ENGINEERING SOFTWARE

Some software programs are dedicated to 3D conception and include reverse engineering modules, when other ones are conceived for this purpose only.

The main distinctive feature of these programs is their capacity to operate information from the existing object. The data scanned or acquired from the object aimed to be reverse-engineered, is used as a base-sketch for the conception of the final design.

2.2.3D SCANNING WORKFLOW

The scanning workflow starts with an object to scan and ends with a final surface model.

Each system has its own distinctive features, but the workflow is essentially identical. The details of the HandySCAN 3D workflow are given in the Laboratory Guide (section3) of the document.

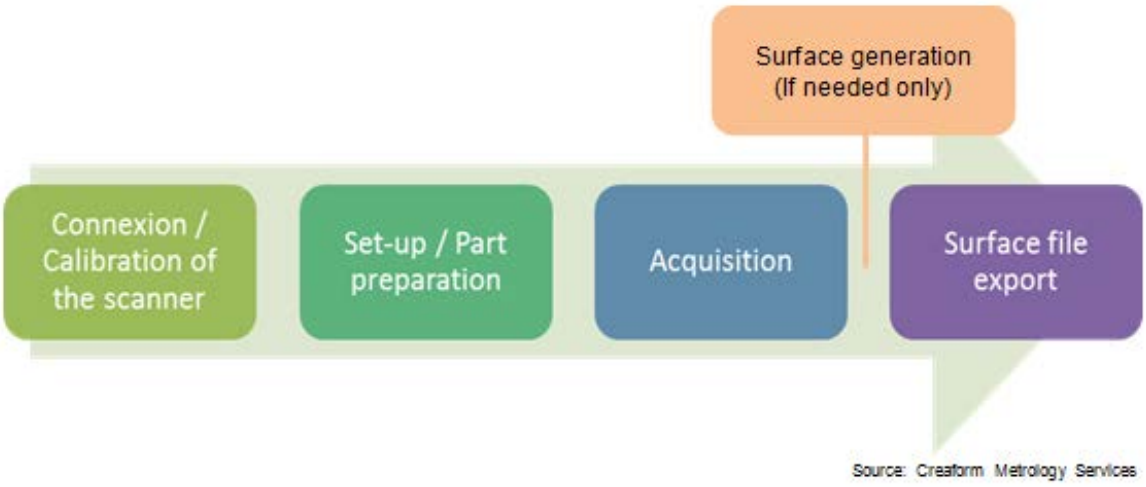


Figure 15: Representation of scanning workflow.

2.3. REVERSE ENGINEERING METHODS

2.3.1. PARAMETRIC REVERSE ENGINEERING

The first method for reverse engineering is mentioned as “design intent” or parametric. The main work is to understand how the object was conceived and to reproduce the conception process.

Some software programs are dedicated to this application. They include actual conception tools with typical geometrical shapes. Basically, the workflow consists in analyzing the several parts composing the object, and creates similar features, as one would do in CAD software (extrusion, revolution, geometries…) to match its global shape.

Purpose

Creating a 3D feature model based on the analyzed design intent and elements from 3D scan data.

Benefit

Can define feature with parameters based on the analyzed design intent and elements from 3D scanned object. The created features can be reused, redefined, modified and translated by controlling parameters.

Useful for

- Manufacturing of a new product with enhanced functions based on existing product.
- Duplicating the target product which does not have a CAD model.
- Analyzing design elements of another part of the product.

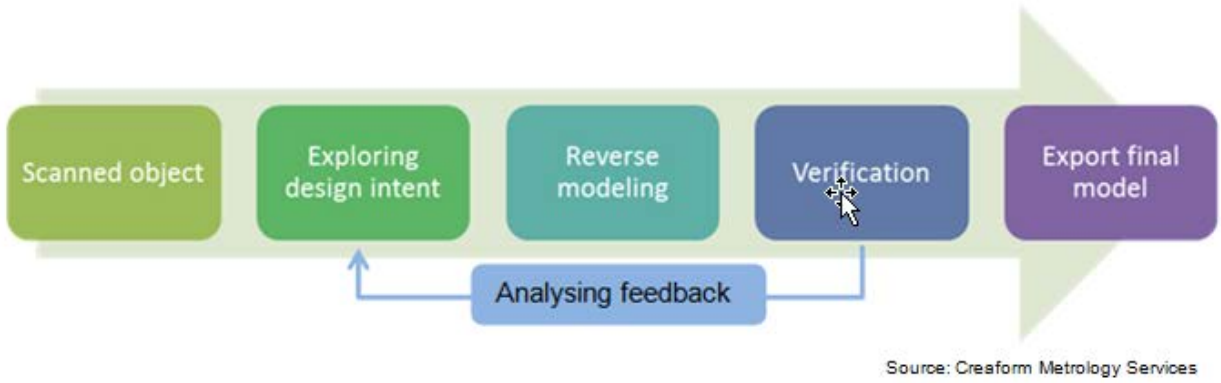


Figure 16: Representation of parametric reverse engineering workflow.

The purpose behind this process is to generate a full parametric model based on the captured 3D scan data. This model will be directly usable in CAD software such as *Catia, Solidworks*, *NX*, or *PTC*… This method usually involves the following steps:

Import

Some software programs include acquisition plug-in, which allow the user to scan directly with the interface and use the resulting mesh file for the reverse engineering process.

Most of the time the STL files are generated from an acquisition program and need to be imported in the reverse software.

Segmentation

An STL file is a neutral file, composed by a mesh of triangles without any actual entities/shapes. Segmentation is an operation splitting the object into different regions/shapes. The software can identify notable features such as planes, cylinders or revolution shapes.

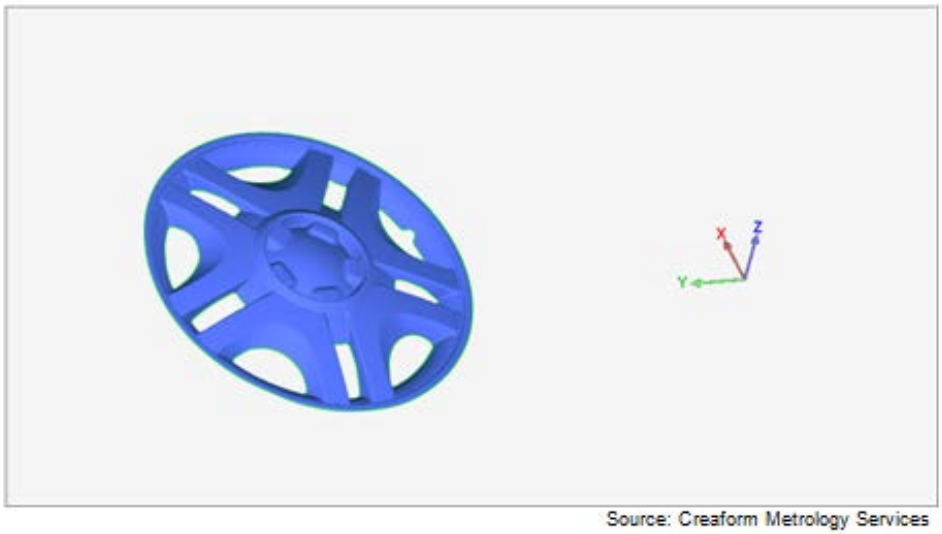
During the reverse engineering, these shapes will be able to be extracted and/or used as a reference for the reconstruction.

Source: Creaform Metrology Services

Figure 17: Representation of object into different regions/shapes (segmentation).

Alignment

In the first place, an STL file has a random position in the coordinate system. The origin point is approximately the first position of the scanner when the scanning operation started.



Source: Creaform Metrology Services

Figure 18: Object before alignment–random coordinate system.

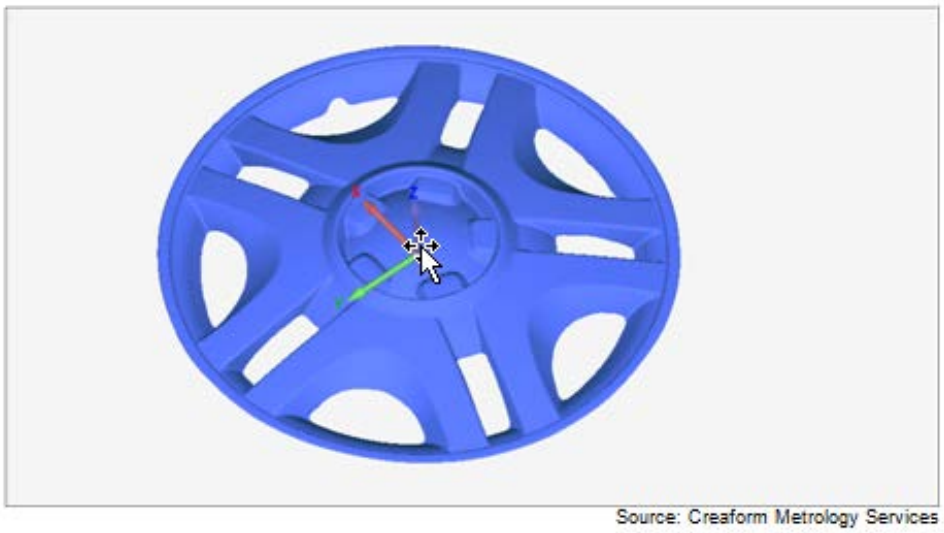


Figure 19: Object after alignment–the object is centered on the coordinate system.

The 3D model is more pleasant-looking when it is well-oriented in space. Moreover, it will ease the reverse engineering process. The operation consisting in creating a new coordinate system based on the mesh is called alignment process. It is not mandatory but strongly recommended.

When there is no particular constraint about the alignment, basic features are usually used (e.g.: 3 planes, plane-line-point).

Exploring Design Intent

For parametric reverse engineering process, the most important part of the work lies in the capacity to understand how the object has been conceived, including the identification of the different features that constitute the object.

Looking at the segmentation and by analyzing the object, a good reverse design involves a good understanding of the design intent. It is essential to identify the main parts of the object and to start the reconstruction with the fundamental features of its structure. The process will step by step lead to more detailed parts to construct.

Feature Modeling

Indeed, parametric reverse engineering uses typical conception features to create a CAD model based on the shape of the STL file. The mesh surface serves as a reference to

make the features match with the actual data. The segmentation is helpful to identify the key elements on the object that may have been used during conception.

When all the elements of the object have been identified and reconstructed, they need to be arranged together in order to fit exactly the shape of the original one.

Source: Creaform Metrology Services

Figure 20: Creation of one entity and repeated circular pattern to create the entire object.

Source: Creaform Metrology Services

Figure 21: Final result.

Accuracy Validation (color map)

A physical object or a scanned 3D model is made up of approximate shapes. Therefore, an object conceived in a reverse engineering process is never the exact copy of the reference. As it is composed of perfect conception features, it is always slightly different.

The reference and the reverse engineering model need to be compared to each other in order to evaluate their relative deviation. A visible and efficient tool to evaluate the quality/accuracy of a reverse engineering is a color map comparison (figure 30). The color coding reveals immediately the deviations between the two models and highlights the critical areas outside tolerance.

After analysis, if the deviations are too high and tolerance is not respected, modifications may have to be applied to solve the problem.

Tips & Tricks

- Sometimes a complete scan is not necessary. Even before scanning the part it can be useful to think about the design intent. It may be possible to reproduce a pattern to construct the complete object. In this case only a portion of the part is needed to be scanned.
- Process step by step: from the most global shape of the part to the small details. Trying to skip stages may cause conception problems, and complicate the potential modifications.
- There are always several ways to do a reverse engineering.

Tips & Tricks

- Sometimes a complete scan is not necessary. Even before scanning the part it can be useful to think about the design intent. It may be possible to reproduce a pattern to construct the complete object. In this case only a portion of the part is needed to be scanned.
- Process step by step: from the most global shape of the part to the small details. Trying to skip stages may cause conception problems, and complicate the potential modifications.
- There are always several ways to do a reverse engineering.

2.3.2. FREE FORM REVERSE ENGINEERING

Free form reverse engineering software programs use different tools than parametric reverse design. In this case, the idea is not to understand and reproduce the conception of the object, but only to create a surface with the exact same shape.

Purpose

This technique has for the main purpose to create3D free form model, based on the optimized mesh from 3D scan data.

Benefit

This process allows extracting, efficiently and rapidly, an accurate freeform surface from the shape of 3D scanned objects.

Useful for

- Creating outer forms of aesthetic model, such as car bodies and outer cover of consumer products.
- Customizing a new product to be fitted for the human body.
- Manufacturing new product based on the human body shape (medical fields).
- Creating animation from digitized shapes.

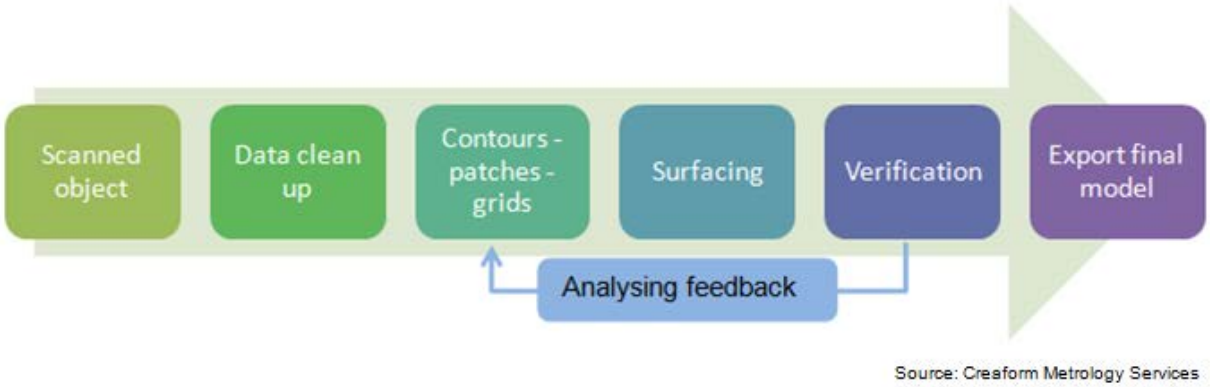


Figure 22: Representation of free form reverse engineering workflow.

Free form surfaces range anywhere from the shape of a rock formation to the body of a car. In these cases, the STL model is used as a reference to build NURBS based on the surface.

For this application, the scan surface needs to be as perfect as possible. Therefore, we can distinguish two main steps for a free form reverse engineering: mesh preparation/optimization and the actual surface reconstruction. These two stages are strongly linked, and a good preparation will ease the surface construction.

2.3.2.1. MESH OPTIMIZATION

Alignment

For free-form reverse engineering, the alignment has only a visual purpose. Usually it is recommended to align the model in order to give it a better orientation; it is easier to work on an object with pre-defined base planes.

The usual workflow for free form reverse engineering consists to create small areas on the surface.

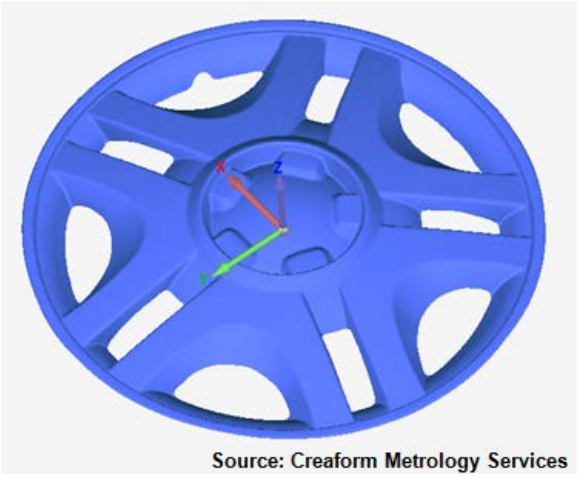


Figure 23: Representation of alignment.

Manifold

As the measuring conditions are rarely perfect, polygonal models may be subject to measurement noise. This noise is mainly visible by small particles/triangles floating over the surface. Manifold operation is used to erase these particles in order to keep only healthy surface.

A second use would be to keep only the main part of the scan, and erase the smaller ones that are not attached to it by triangles.

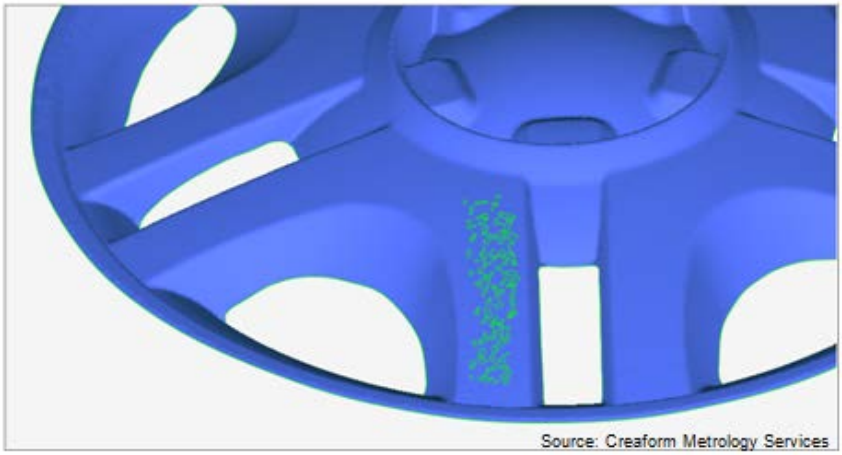


Figure 24: Representation of measurement noise (green triangles).

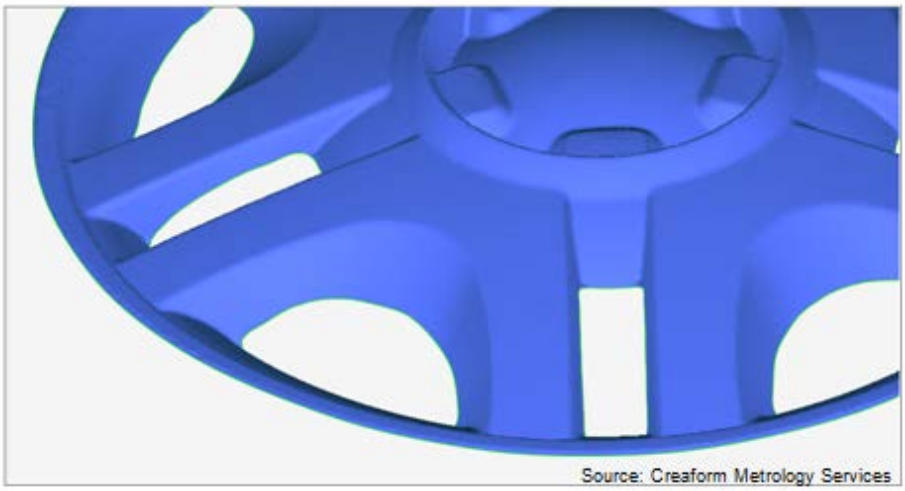


Figure 25: Floating particles gone after manifold operation.

Fill Holes

If some data are missing, 3D software uses adjacent surfaces in order to fill the holes with triangles. Usually the software offers three ways to fill a hole: complete hole, partial and bridge.

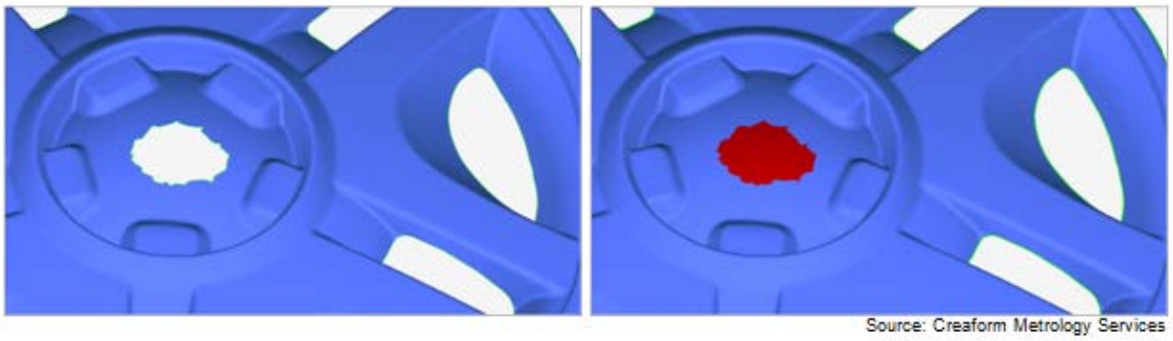


Figure 26: Damaged part/Complete fill hole.

Figure 27: Damaged part/Partial fill hole.

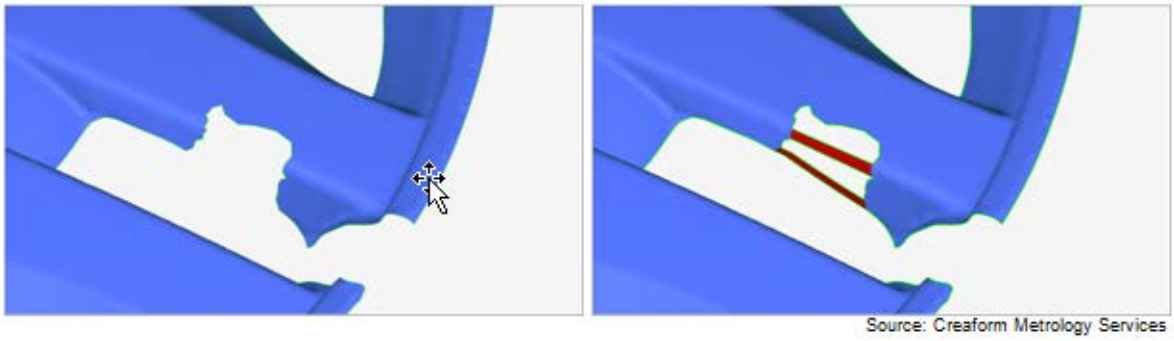


Figure 28: Damaged part/Bridge fill hole.

Assembly: Combine, Merge, Boolean (optional)

A scan cannot always be done in one operation. If the object is very large, has a complicated shape or requires a high definition scan, the data may have to be acquired in several scans. These separated parts of scan data can be merged together afterwards to create a single file.

There are several methods to assemble the data: **combine** (scan parts are added up), **merge** (common parts are overwritten) or **Boolean** operation (cut, intersect, union) and each method has a different purpose and result.

Combine

When combined, two parts of the scan are simply added up to each other. The mesh is not modified, but the resulting mesh includes all the data from the previous ones which have been combined.

Merge

Like combining, merging scans creates one single mesh out of many separated ones. The difference lies in the way the scans will be merged. When merged together, adjacent surfaces will be mixed up in order to create only one surface.

Boolean: Like on any other 3D objects, the typical Boolean operations can be applied to scan data. Common surfaces can be cut, intersected, and scan objects can be added or subtracted to each other.

Mesh Optimization: Smooth & Noise Reducing

Average measurement conditions or bad surface aspect can make noise during acquisition. This can be materialized by rough areas on the surface. Reducing the noise consists in deleting most of the visible noise/spikes. It is quite aggressive local or global smoothing operation.

Smoothness operations can also be used in esthetic purpose, for a better-looking mesh without lumps.

Mesh Optimization: Decimation (optional)

The size of an STL file is proportional to the number of triangles that it contains. Therefore, a high-resolution mesh file can be quite big, and it can be very convenient to optimize its size. By default, the triangles density is identical on the whole mesh. Yet on some areas, bigger triangles could define exactly the same surface as smaller ones, without any accuracy loss. Considering this, the more flat areas can be described by a lower amount of triangles.

This operation can be done manually, as the triangle count/density can be changed on a selected area. But most of the programs include automatic decimation operation. Strongly curved and flatter areas are identified, and the density is adapted for each.

Source: Creaform Metrology Services

Figure 29: Representation of decimation process.

Final Mesh Optimization

A free form reverse engineering uses the mesh as a reference to build NURBS (Non-uniform rational basis spline). The surface has then to be as clean and smooth as possible.

Dedicated options are usually available in post-treatment software programs, which mainly aim to enhance the quality of the surface. Among them, the most important ones are smoothing and noise reduction/spikes removing. All of them are globally smoothing tools, with different level of impact on the mesh.

Warning: these tools are to be used with restraint. As they modify the inherent polygonal structure of the mesh, deviations may result between the original model and

the optimized one. These deviations can decrease the accuracy of the reverse engineering.

Tips & Tricks

- The cleaning process needs to be done gradually. First eliminate the defects without strongly modifying the mesh structure (manifold, filling holes). The smoothing operations are to be done in a second time.
- If possible, try to work with a single mesh file. Merging in a post-treatment software program may create deviation and mesh defects.
- Use the “aggressive” functions wisely: smoothing operations will modify the mesh structure itself, including the object shape. Getting a smooth and clean mesh is important, but be careful not to create too much deviation with the original model.
- As mesh optimization may have modified the shape, always compare the result with the original scan during the accuracy validation step.

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- As mesh optimization may have modified the shape, always compare the result with the original scan during the accuracy validation step.

2.3.2.2. REVERSE DESIGN

The typical workflow for free form reverse engineering consists in creating small areas on the surface. There are several steps, dividing the object in smaller and smaller areas and leading to small surface features wrapping up the object.

Contours

The first step consists in drawing lines following, as much as possible, the main curvature lines on the object. The contours will define the areas with low curvature level and aim to isolate the main remarkable shapes on the object.

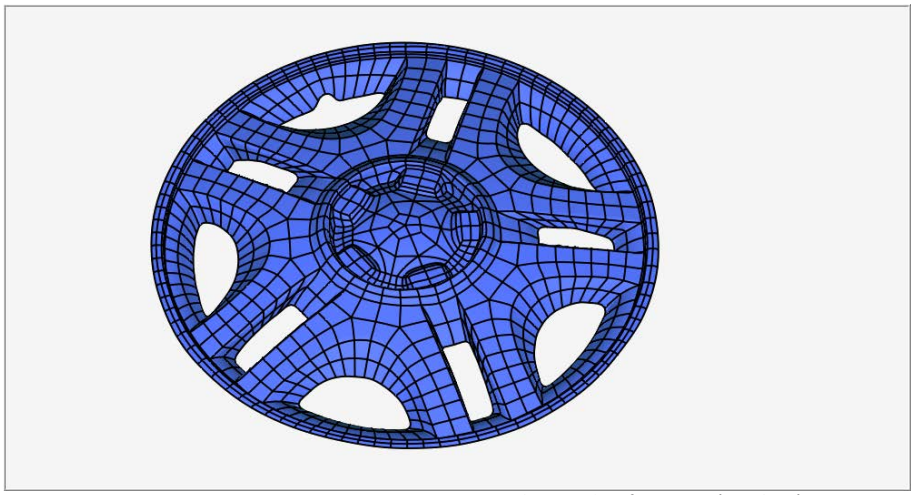
Source: Creaform Metrology Services

Figure 30: Representation of contours.

Patches

On the second step, divided areas are smaller than the ones drawn by the contours. They create a pattern of square-shaped areas. This task can be tricky, as the patches' distribution will establish the quality of the reverse. Patches need to have approximately equal size, look like squares and respect the curvature defined by the contours.

Note: an ideal pattern of patches would be a perfect grid with similar squares.

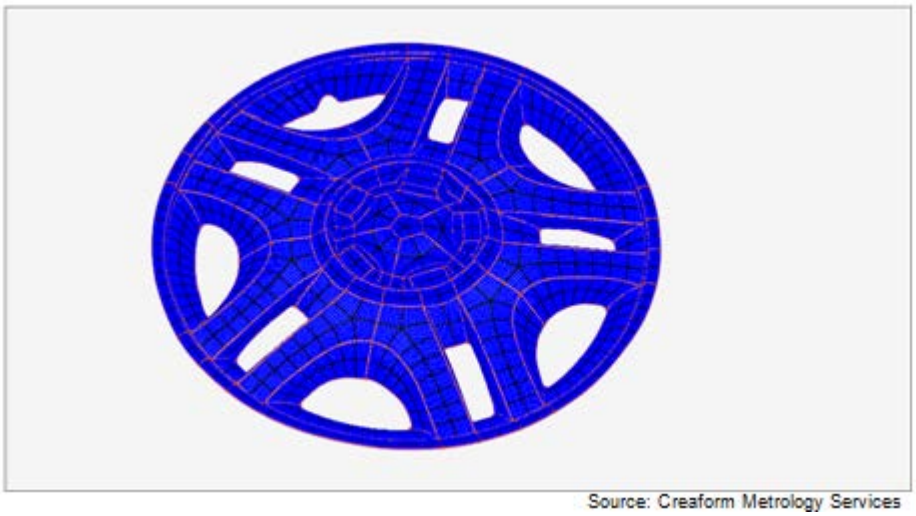


Source: Creaform Metrology Services

Figure 31: Representation of patches.

Grids

Grids are the last degree of division before the actual surface creation. Each patch is divided into small squares, according to a division density factor. Depending on the software program, the density can be adapted to each patch or constant all over the object. These small squares will be filled with surface elements to create the final surface.

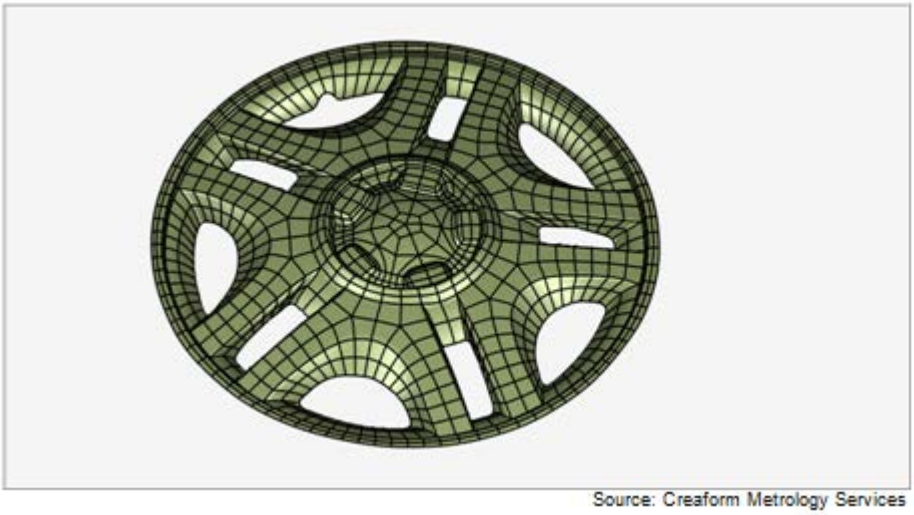


Source: Creaform Metrology Services

Figure 32: Representation of grids.

Surface

Once the grids are drawn, most of the work is done. The last step is creating the NURBS on the surface, by wrapping surface elements over the grids squares. The final surface can at this point be exported as a CAD file in various formats, such as IGES or STEP.



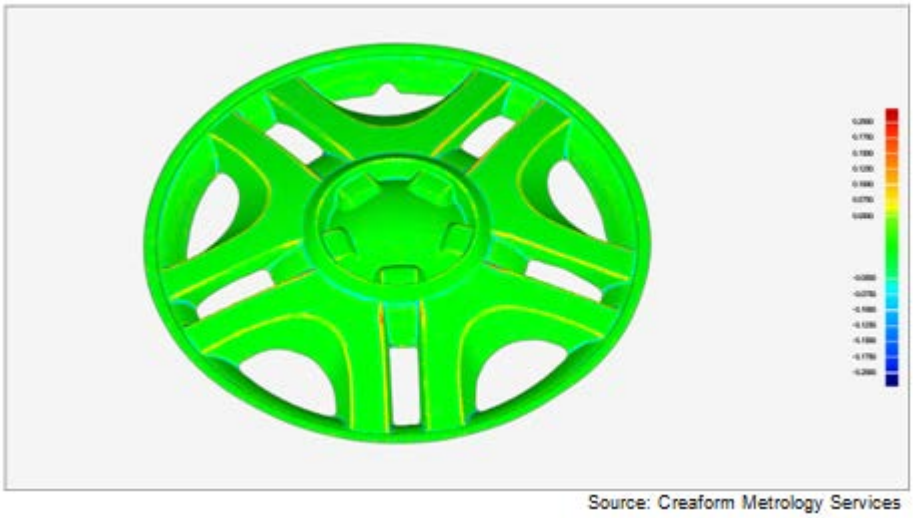
Source: Creaform Metrology Services

Figure 33: Representation of surface.

Accuracy Validation

Even with an accurate surfaces reconstruction, the resulting file is never exactly consistent with the scan data. Therefore, an accuracy validation is needed to assure the quality of the reverse engineering.

Like for the parametric reconstruction, the color mapping method is a good visible way to identify the defected areas.



Source: Creaform Metrology Services

Figure 34: Representation of color mapping process for accuracy validation.

Tips & Tricks

- The first step before starting any contours drawing on the object is to check the mesh quality. Having a global overlook on the part to check any defect will save time and avoid starting the whole process again.
- Try to imagine the patches pattern when drawing the contours. It helps to divide some areas in a similar way in order to ease the different areas to match together.
- If possible the patches have to look like a grid. It will give better results at the end of the reverse design process.

2.4.3D DATA CLEAN UP AND PREPARATION

Cleaning a 3D file consists in modifying the polygonal structure of the model, in order to further improve the overall quality of the model. The different tools may either affect the entire model or only selected areas. Other tools simulate manual processes and involve some interactions with the user (e.g.: sanding off a particular unwanted detail).

This process is usually gradual, using tools with increasing order of influence on the object geometry. Basically, first corrections are made on local defects, such as isolated triangles or small holes, and in a second time global improvements.

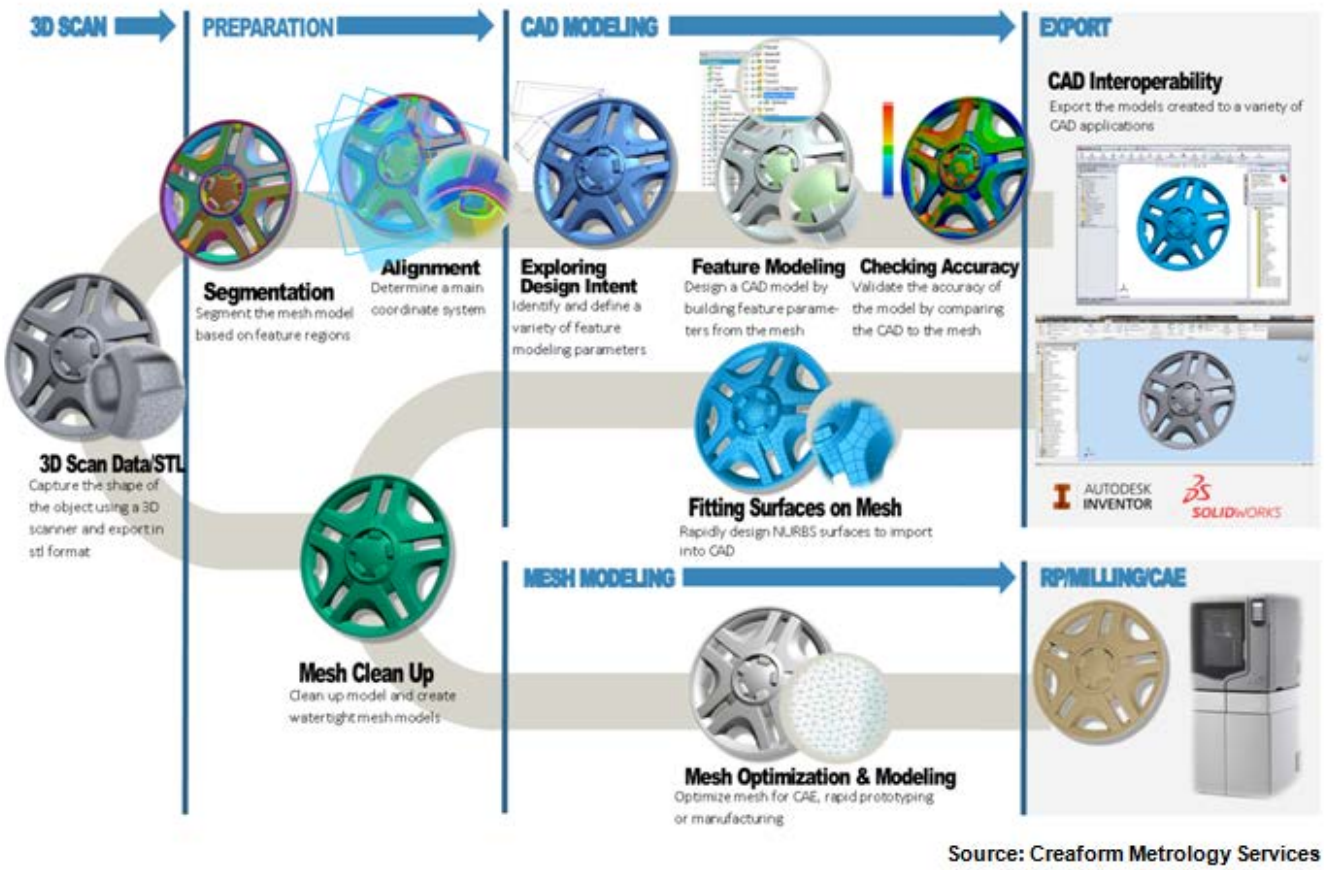
The level of clean-up and preparation on an object is defined by the type of reverse engineering to be done (parametric reverse engineering or free form reverse engineering).

As the parametric reverse engineering main goal is to understand how the part (object) was conceived and to reproduce the conception process with the actual design functions. The surface of the object doesn't need to be perfect, nor needs the damaged areas to be completed. In the case of the free form reverse engineering, the reverse design is based on the total surface of the

object. As it should be flawless, it is mandatory in most cases, to make cleaning and preparation in order to save time and ensure the quality of the final model.

2.5. TYPICAL WORKFLOW

In order to use 3D scan as part of digital processes, different approaches can be used, as illustrated below:



Source: Creaform Metrology Services

Figure 35: Representation of typical reverse engineering workflow.

CONCLUSION

Discovered centuries ago, reverse engineering is now strongly used in many industries. As part of the product lifecycle management (PLM), reverse engineering is an important step of the product development and the appearance of 3D technologies on the market has definitely allowed increasing and improving this practice in industries.

Reverse engineering is now facilitated by the use of 3D technologies and software. Indeed, the 3D technologies and software available today offer a range of possibilities and, over the years, progresses made in this field are huge. Creating products trustworthy and accurate is now possible; product design is greatly facilitated, products are reliable, more accurate and improved.

In addition, technical skills and knowledge have a lot advanced over the years in this field. Although the industrial use of 3D technologies is a common practice for reverse engineering, quality control and inspection, 3D technologies are increasingly used in various other applications: multimedia, entertainment, museology, heritage preservation or in virtual reality. The possibilities are numerous and unlimited.

The application that is currently emerging with its growing popularity is the 3D printing which provides a lot of opportunities. Associated with the use of 3D technologies and CAD software, 3D printing is creating a real craze in the industry. The 3D printers are available and accessible; they facilitate the conception of products and allow accelerating the manufacturing process.

Some will say that additive manufacturing (or 3D printing) is an important turning point, an incredible revolution in manufacturing but certainly, this is a major step forward for manufacturing.

3. HANDYSCAN 3D LABORATORY GUIDE

3.1. QUICK START

1. Connect the Express Card to the computer

2. Connect the Firewire cable into the Express Card

3. Connect the power supply into the FireWire cable

4. Plug the power supply to an electric source

5. **At the very end**, connect the elbow shaped end of the FireWire into the scanner.

6. Once the scanner is connected, launch the Creaform acquisition software VXelements™.

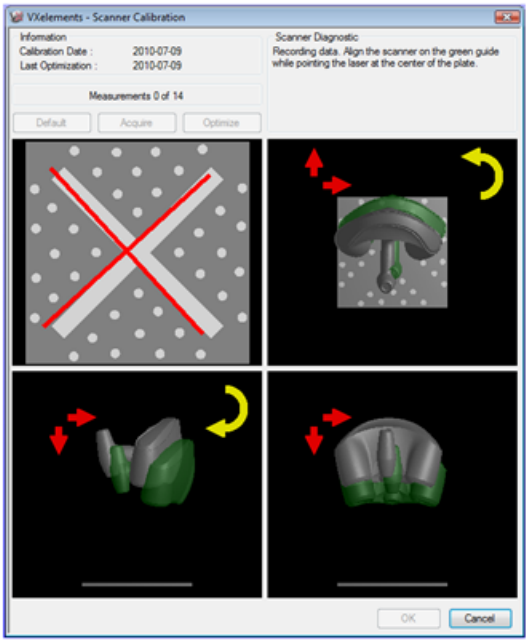
3.2. SYSTEM CALIBRATION & OBJECT PREPARATION

3.2.1. CALIBRATION PRINCIPLE

Calibration is made using a known reference. When on the field, calibration may be affected by changes in the environment of the sensor. These changes are mostly due to variations in temperature or pressure, and result in modifications of the mechanical configuration. Even under normal use, the HandySCAN 3D must be calibrated on a regular basis.

3.2.2. CALIBRATION PROCEDURE

The glass plate is used to compensate for these changes. VXelements™ software optimizes the calibration in order to get back to the initial measuring features. The calibration procedure consists in bringing the scanner to the positions highlighted by the green shadow while keeping the laser cross in the white portion of the calibration plate. The actual position of the scanner is shown in grey (Figure 36).



Source: Creaform Metrology Services

Figure 36: Representation of the calibration procedure.

3.2.3. OBJECT PREPARATION

3D scanning means acquiring the shape of an object. The object to be scanned needs to be as clean as possible because all the defects/dirt/dust will be seen on the resulting scan data. A good preparation is essential for good scanning result.

3.2.3.1. SURFACE PREPARATION

For better digitization, any object that is shiny, black, transparent or reflective (like mirrors and shiny or metallic surfaces) must be covered with white powder to obtain a mat finish getting nice and accurate results.

3.2.3.2. TARGETS APPLICATION

The HandySCAN 3D is positioned relatively to the object with reflective targets. These targets should be positioned in an organized fashion to make sure that the surface is free of blank spots and that the scanner will be well positioned any time (Figure 37). This is true even if randomization is necessary to create unique feature patterns.

Source: Creaform Metrology Services

Figure 37: Representation of targets application.

Tips & Tricks

- Average distance between targets: from 2 to 10 cm (0.7 to 4 in).
- Shorten the distance between targets on high-curvature areas.
- Avoid damaged, greasy, dusty, dirty or hidden targets.
- Avoid to align targets too perfectly (doesn't allow proper triangulation).
- Do not put targets close to edges and/or detailed areas: >5mm (0.2 in) from the edge.
- Apply a regular density of targets; do not create isolated groups of targets. Triangulation implies at least 3 targets seen at once: the targets pattern needs to take this parameter into consideration.

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3.3. DATA ACQUISITION

When the object has been entirely prepared for the 3D acquisition, the scanning part (data acquisition) can start. Depending on the object complexity, some precautions have to be taken,

and it can be more or less easy to get the entire surface of the object. The output file will be a point cloud or mesh file, representing the surface of the scanned object.

NB: some scanners use point cloud technology. In this case, the 3D model may need to be transformed into a polygonal model. Using a scanner making a polygonal acquisition spares this post-treatment step.

3.3.1. SENSOR ORIENTATION

When looking perpendicularly at a target, the image captured by the cameras is a perfect circle. It is then easy to calculate the center of the circle with a high level of accuracy.

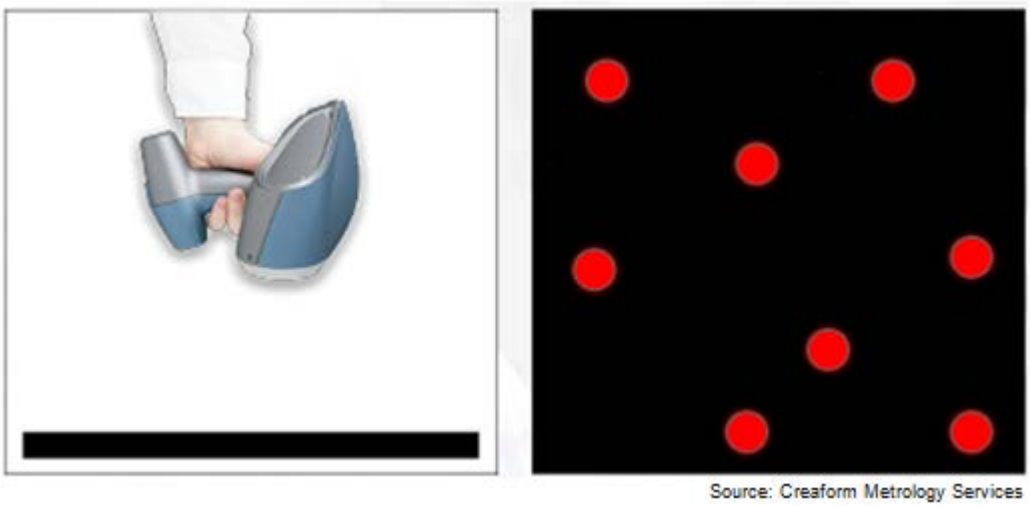
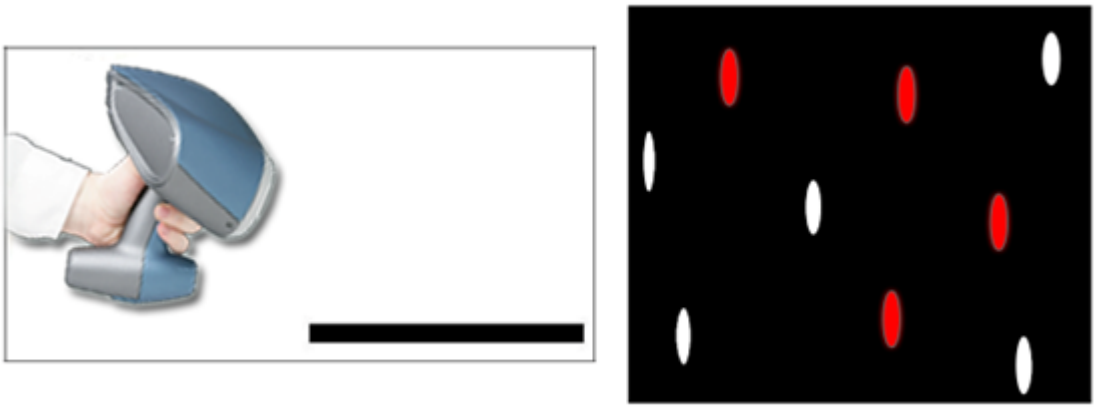


Figure 38: Representation of sensor orientation (perfect circle).

On the other hand, when the angle of incidence is acute (closer to 45°), the image of a target captured by the cameras is an ellipse. The influence of the error in the calculation of the center of the ellipse is greater than in the case of a circle. So, the accuracy of the positioning model will be higher with greater angles of incidence.



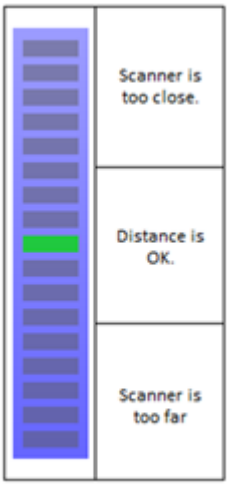
Source: Creaform Metrology Services

Figure 39: Representation of sensor orientation (ellipse).

3.3.2. SENSOR DISTANCE

During the digitization, a meter displayed on the left of the screen indicates the distance between the scanner and the object (Figure 40). This meter is also represented on the scanner by 3 LED located on the upper part of the scanner (red, green, red).

Average distance: 30cm +/- 15cm.



Source: Creaform Metrology Services

Figure 40: Distance meter in VXelements™

3.3.3. SCANNING TECHNIQUE

1. To scan an object efficiently, it is very important to visualize the different sections and areas on the object.

2. Next step is to visualize a squaring more or less dense depending on the required level of details for each area. This squaring will be an indication of the speed to use when sweeping the surface in that area. Section containing small details will require slower sweeping of the surface with the HandySCAN 3D.

3. Data acquisition can start. The objective is to reproduce previously visualized path and density with the laser cross. An optimal movement of the HandySCAN 3D will have the laser cross move obliquely and not parallel to the surface. This allows minimizing required movements to acquire enough good data.

4. While sweeping the surface, there are also some rules to follow that will make your scanning process easier and more efficient. It is very important to move the scanner slowly over the surface and to avoid rapid wrists movements. It is important to imagine an optimal zone which size will depend on the level of details required and on the size and geometry of the object.

Tips & Tricks

- Adapt the resolution to the level of detail expected and to the object size (higher is the resolution, slower will be the scanning operation)
- For a large part, make the targets acquisition first, it will ease the surface scanning process and avoid accuracy problems.

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