REVERSE ENGINEERING OF TURBINE BLADES WITH INTERNAL FEATURES

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RESUMEN

La competencia internacional en la industria aeroespacial ha forzado a las compañías a re-diseñar componentes antiguos para poder reducir el tiempo de desarrollo de nuevos productos. Una de las metodologías para enfrentarse a estos desafíos es el uso de la Ingeniería Inversa (RE). Debido a esto, el enfoque de este trabajo es presentar un breve estudio del estado del arte en tecnologías de Ingeniería Inversa y un caso de estudio basado un alabe de turbina hecho de Inconel 718. Un equipo de tomografía computarizada (CT) fue usado para el estudio de las secciones internas de la pieza. Los resultados muestran varios errores en los escaneos de la tomografía que hacen necesario el uso de otras técnicas de medición. Debido a estos resultados con los escaneos del tomógrafo, la metodología presentada no puede ser usada para operaciones de Ingeniería Inversa de piezas con altas tolerancias. De igual manera, se proponen líneas de investigación para poder abarcar este tipo de piezas.

ABSTRACT

The international completion in the aerospace industry has forced the companies to re-design old components in order to reduce the development time of new products. One of the methodologies to address this issue is the Reverse Engineering (RE). Due to this, the scope of this work is to present a brief study of the state of the art in RE technologies and the reverse engineering of a turbine blade made of Inconel 718 including the reconstruction of its internal cooling system without destroying the turbine. A computerized tomography equipment (CT) was used for the internal features of the work piece. Results show that several errors in the CT scans makes necessary the combination of this technology with other measuring techniques. Due to this issues with the CT scanning, the presented methodology is not suitable for Reverse Engineering operations of pieces with high tolerance requirements. Future work is presented in order to address this issues.

INTRODUCTION

Nowadays several industries have re-engineer their design and production processes in order to achieve a higher efficiency together with a reduced development cost; as one solution for facing the challenge that represents global competition in the market place. An example of one of this industries is the aerospace industry which is reducing the number of large systems developed from scratch. Instead of this, the new aircraft components and parts are created by modifying and combining existing subsystems. This changes range from modifications in the available design data and methods to changes in manufacturing hardware and software technologies [1].

An example of the methodologies for obtaining information of these various components is the Reverse Engineering techniques (RE). The RE can be used for several operation which varies from analysis and simulation to design of new components based on physical mock-ups and in some cases it even includes rapid maintenance operations. Therefore, reverse engineering of aerospace components plays a crucial role in the reconstruction of mathematical models for FEM analysis, rapid prototyping and re-engineering procedures [2] [3].

Due to this reasons, the present work focuses in the development of a RE methodology for an aerospace turbine blade made of a nickel super alloy. This kind of components are formed with surfaces with freeform shapes, which may be classified as complex geometrical features that cannot be represented as a combination of planes, spheres, cylinders or other simple shapes. Due to their aesthetic or functional reasons, these shapes are of great interest in several applications such as optics, turbine blades or even aircraft fuselages. It is important to notice that due to the functional nature of these shapes in the functioning of turbine blades, geometrical deviations in the manufacturing process may cause inefficiencies that can cause waste of large quantities of energy. At the same time, the smallest fault during the design or manufacture of such components can lead to a catastrophic system failure. Therefore the implementation of all means of precautions available is paramount to ensure system reliability and blade integrity without compromising economic aspects [4].

Turbine blades are subjected to extreme working conditions, were the temperature may be raised as high as 1500°C, with high mechanical and thermal stresses. Also, in order to overcome these conditions, turbine blades are designed with and internal cooling system made out of several veins. With this system, cooling air at around 650°C is extracted from the compressor and passes thru the air foils, lowering the temperature of the blade to approximately 1000°C [5] [6].

Currently, most of the research work in the area of Reverse Engineering focus on the accuracy of the scanning process or in the development of reconstruction procedures for complex external surfaces. Due to this, the present work aims to develop a high accuracy method to perform reverse engineering operations in complex freeform components,
taking in consideration the internal features of the structure of the work piece without the need of destroying the piece.

**RESEARCH FOCUS**

The structure of the work starts with a brief study of the state of the art of the RE used through the project, as well as a description of the proposed methodology. The experimental procedure, based on a case study of a small turbine blade of a jet engine with a cooling system is presented. Results of the procedure and are discussed and an outline for suggested future work is presented.

**LITERATURE REVIEW**

The main task of RE is the reconstruction of an object whose surface is composed of a number of surfaces of different shapes. The basic process stages are [7]:

- Coordinate measurements.
- Surface approximation.
- Use of data for specific tasks.

In order to ensure the accuracy and precision of the performed measurements, several RE methodologies are based in the scanning of the work piece with different measurement technologies (i.e. CMM and optical systems). An example of this is a RE methodology specifically design for the work in turbine blades. The methodology consists in the measure of the work piece by several measuring technologies. After this, several reference characteristics are generated based in a local coordinate system (i.e. a symmetry axis, a [z] plane and a series of points). Once with this information, each scanning line of each of the technologies is analyzed in order to generate a more accurate 3D model [8].

Other methodologies focus in the use of the data generated thru RE. An example of this is the methodology patented by “General Electric” (GE), in which the data obtained from the RE process is used to generate a “master 3D model” of certain work piece. Such parametric model is editable, which allows the designer to re-engineer the piece in order to improve it. With the new model, the designer is capable of generate not only a better product, but also is able to design the required tools and elements used in the fabrication of the new part (i.e. cutting tools, fixturing equipment), as well as the NC programs for the manufacture of the work piece [9].

This brief study of the state of the art allow us to see the use of the data obtained thought the RE process. It can be noticed that the final objective of the RE procedures is to support the design and re-design operations of the products, while improving the product quality and reducing the development time.

The proposed methodology uses 2 different measuring technologies for the coordinate measurements of the work piece and the internal structure. This sections presents a small briefing in measuring technologies used in aerospace industry, focusing specially in the technologies used for the project: optical scanner and computerized tomography.

Also, a small briefing in Non Uniform Rational B-Splines (NURBS) surfaces is presented due to its use through the RE procedure.

**Measuring technologies.**

One of the most important tasks inside the RE procedure is to measure the piece, in order to obtained the starting data for the development of a reconstructed 3D model. Due to this reasons, the generation and analysis of measuring data plays a key role in the development of this work.

![Image of measuring technologies](image)

**Figure 1. Classification of measuring technologies according to the size of the aerospace component [4].**

Figure 1 shows a classification of several measuring technologies according to the size of the aerospace piece to be inspected. These components can be classified in 4 sectors: large, medium, small and micro components [4].

The focus of this work is a small component with freeform shapes, and therefore the main focus of this literature review is the study of the optical scanner and computerized tomography technologies.

**Optical Scanner.**

Triangulation sensors in optical scanners have become frequently employed for in-process metrology in a wide variety of industries that can go from the automotive to the medical industry. Figure 2 shows the basic principle of a triangulation sensor.

![Image of triangulation sensor](image)

**Figure 2. Principle of the triangulation sensor [8].**

The main components of such systems are a collimated light source (generally a laser diode) and a detector units consisting of an imaging lens and a position sensitive diode (PSD). The optical axes of the light source and the image lens forms a fixed angle and the object surface is brought close to the point in which both axes intersects and the
diffuse reflection of the light spot on the work piece surface is image to onto the detector. Compared to mechanical systems (i.e. a CMM), optical methods often can acquire more data in less time, with the advantages of measuring the part without contacting the piece [8].

These kinds of technologies have been used in Reverse Engineering procedures, but the scanning result may not achieve a high accuracy and can present a bigger uncertainty when compared to mechanical systems [9]. Another disadvantage of optical systems comes from the preparation required for the measurement of some translucent or reflective parts. Such preparation requires spraying parts, which affect the accuracy of the measurement in a range between 3-5 µm [4].

In order to address these issues, the combination of optical measurements and mechanical systems, even at different times and locations, can yield a highly accurate 3D reproduction of the physical object, while reducing the time required for the data acquisition process [10]. Also, an international effort in order to ensure the quality of the measurements and scans performed is being carried out through the development of international standards and guidelines, such as the German guideline VDI 2617 [11].

For this work, an optical system based on a triangulation sensor was used in order to scan the external surface of the work piece.

**Computerized Tomography.**

Recently, Computerized Tomography (CT) has become an accepted inspection tool for several industrial applications. What makes this kind of technologies preferable to the most effective [16]. This is due to several reasons, which include, but are not limited to:

- They offer a common mathematical form for representing and designing both standard analytical shapes (conics, squares, etc.) and free-form surfaces.
- By manipulating the control points as well as the weights, NURBS provide the flexibility to design a large variety of shapes.
- Evaluation is reasonably fast and computationally stable.

However, NURBS have several draw backs, such as:

- Extra storage is needed to define traditional curves and surfaces.
- Improper application of the weights can result in a very bad parameterization, which can destroy subsequent surface constructions.
- Fundamental algorithms, such as inverse point mapping are subject to numerical stability.

The mathematical definition of a NURBS curve is a vector-valued piecewise rational polynomial function of the form (Eq. 1):

$$ C(u) = \frac{\sum_{p=0}^{n} w_p N_{p,k}(u)}{\sum_{p=0}^{n} w_p N_{p,k}(u)} \quad (\text{Eq. 1}) $$
Where \( w_i \) are the so-called weights, \( P_i \) are the control points (just as in the case of non-rational curves), and \( N_{i,p}(u) \) is the normalized B-spline basis functions of degree \( p \) defined recursively as (Eq. 2) (Eq. 3):

\[
N_{i,0}(u) = \begin{cases} 1 & \text{if } u_i \leq u \leq u_{i+1} \\ 0 & \text{otherwise} \end{cases} \quad \text{(Eq. 2)}
\]

\[
N_{i,p}(u) = \frac{u-u_i}{u_{i+p}-u_i} N_{i,p-1}(u) + \frac{u_{i+p+1}-u}{u_{i+p+1}-u_{i+1}} N_{i+1,p-1}(u) \quad \text{(Eq. 3)}
\]

Where \( u_i \) are the so-called knots forming a “knot vector” (Eq. 4):

\[
U = \{u_0, u_1, ..., u_m\} \quad \text{(Eq. 4)}
\]

The degree, number of knots, and number of control points are related by the formula \( m = n + p + 1 \). For non-uniform and non-periodic B-splines, the knot vector takes the form (Eq. 5):

\[
U = \{\alpha, \alpha, ..., \alpha, u_{p+1}, ..., u_{m-p-1}, \beta, \beta, ..., \beta\} \quad \text{(Eq. 5)}
\]

A NURBS surface is the rational generalization of the tensor product non-rational B-spline surface and is define as follows (Eq. 6):

\[
S(u, v) = \sum_{i=0}^{m} \sum_{j=0}^{n} w_{i,j} P_{i,j} N_{i,p}(u) N_{j,q}(v) \quad \text{(Eq. 6)}
\]

Where \( w_{i,j} \) are the weights, \( P_{i,j} \) form a control net, and \( N_{i,p}(u) \) are the normalized B-spline of degree \( p \) and \( q \) in the \( u \) (Eq. 7) and \( v \) (Eq. 8) directions, respectively, defined over the knot vectors:

\[
U = \{0, 0, 0, 0, u_{p+1}, ..., u_{m-p-1}, 1, 1, 1\} \quad \text{(Eq. 7)}
\]

\[
V = \{0, 0, 0, 0, v_{q+1}, ..., u_{s-q-1}, 1, 1, 1\} \quad \text{(Eq. 8)}
\]

Where the end knots are repeated with multiplicities \( p+1 \) and \( q+1 \) respectively, and \( r = n + p + 1 \) and \( s = m + q + 1 \). The top section of Figure 4 shows a representation of NURBS curves that lie in a 2D Euclidean plane and a NURBS surface is depicted on the bottom section of Figure 4 [17].

Several software for the development of parametric CAD models thru the use of NURBS surfaces exist today. According to their procedure workflow, they can be classified in the following [18]:

- 1st Generation software: It is based on the principle of dissecting the point cloud in different planes and generates the NURBS curves in each plane. After, the curvature of the points is approximated by a network of Bezier curves.
- 2nd Generation software: A polygon surface is generated from the point cloud by connecting the adjacent points with linear vertices. After, a NURBS patch network is fit to the surface. This latter data can be used as a template for the generation of a parametric CAD model.
- 3rd Generation software: This kind of software allows the generation of parametric CAD models directly from the point cloud, describing the relationship of the various entities.

**METHODOLOGY**

The proposed RE methodology is depicted in Figure 5.

The procedure begins by obtaining a reference system
through the development of a special fixture in order to be able to use it as a base for the digitization and measuring procedures. The measurements are then carried on an optical scanner, and CT equipment.

After the measurements were made, a reconstruction of the 3D model was performed through the use of NURBS.

**EXPERIMENTAL PROCEDURE**

Figure 6 shows the “inner section” (left) and “outer section” (right) of the turbine blade made of Inconel 718 with an internal cooling system that was used for this particular case study. As explained before, the experimental procedure begins by obtaining of a reference system through the development of a special fixture in order to be able to use it for the digitization and measurement procedures. The reference systems consist in 3 steel spheres of 10 mm in diameter attached as depicted in Figure 7.

![Figure 6. Turbine blade used for the present work (left side: inner blade, right side: outer blade)](image)

![Figure 7. Turbine blade with reference spheres and fixture system.](image)

After the reference system was attached to the piece, six different scans where performed in the optical scanner: three for the inner blade of the turbine and three for the outer blade section. A 3 Shape optical scanner, model Q800 was used for this scan.

The scan procedures were carried with 6 scans of 60° each at 3 different angles of the work piece: 75°, 45°, and 10°. “Convince Analyzer” software was used in order to properly mix and align the data from each of the scans of the inner blade section with the ones of the outer blade section. During this procedure, any points generated by noise are deleted as well as any point clouds that did not belong to the reference system or the turbine blade, such as the points of the fixture system.

After the alignment, and for the purpose of to reduce the size of the data any sections that where unnecessary the RE processes were removed and the mesh was edited in the GOM inspection software. Figure 8 shows the final *stl file used for the RE process.

![Figure 8. Mesh used at RE process.](image)

For the CT measurements a Metrotom 1500 scanner of the company Carls Zeiss was used. The temperature during the measuring scans where reported to be between 19.5°C and 19.8°C. Each scan toked 1 hour to be performed.

After the scans were performed, a surface determination procedure was done. The procedure starts with the definition of a sample of what should be the background and the material, based on 2D images of the piece. Next, the program automatically makes a first iteration of what the background should be, the user makes a refined selection based on what the surface should be. This is accomplished through the manipulation of 3 “limit bars” placed on top of a histogram of the points in the file. By the manipulation of these values the user is able to determine the surface based on the x-ray 2D images of work piece, as showed in Figure 9.

![Figure 9. Surface characterization procedure.](image)

At this point it is important to mention that from a total of 5 scans that where carried on, only 3 of them were able to be used during the project due to the scattering of the x-ray beam.

After the surface characterization of the data is finished,
an alignment on the CT images is performed in the same fashion as for the optical scans. Once the alignments were performed, a surface extraction was realized in order to be able to export an *stl file to be used in the following works.

Once the scans where performed, the mesh was edited in the GOM in order to reduce the size of the data by removing any sections that where unnecessary the RE process. Figure 10 (left) shows the image of the file after the removing of these sections, while the right side of Figure 10 shows the mesh for the internal cooling system of the turbine blade.

Using the reference spheres and the surface of the outer blade, both the mesh obtained by the optical scanner and the Ct scanner are aligned and combined in order to be exported as an *stl file to a specialized RE software. It is important to mention than in order to develop an appropriate technique for the reverse engineering procedure, the piece was divided in three sections accordingly with their geometrical characteristics:

- Fir tree: Freeform and prismatic geometry.
- Blade: Freeform geometry.
- Inner section: Prismatic geometry.

Accordingly to each of the geometrical characteristic, the use of NURBS surfaces was necessary in areas where a freeform surface was located. Figure 11 shows the data of the optical scanner used for the RE procedure (left), the data of the CT measurements that was used (right) and the general division of the work piece.

The surface generation procedure begins with the triangulation of the points for the generation of a surface composed of polygons (*stl), which points are described in a purely numerical way. This is in contrast of the way a CAD model represents its surfaces, which is in an analytical fashion based on equations.

The RE software uses the numerical data of each of the polygons in order to construct analytical equations of “bilinear surfaces elements” (i.e. straight lines or polygonal curves of first order). Such bilinear elements are generated in the form of NURBS curves. Once all the surface is divided in bilinear elements, such elements are merged in order to generate a closed solid or a closed solid surface [21].

In order to be able to generate a solid for the blade section of the work piece, NURBS surfaces were used. The surfaces were created by using a control net based of points automatically extracted from the point cloud shown in the Figure 12. Once the surface was generated, a solid was created in order to perform a subtraction Boolean operation using the surface as a tool. It is important to mention that in case a of a great density of control points in the net, the freeform surface might not be suitable to the real surface, due to the several changes in the curvature of the NURBS.

In order to address to this issue, a surface with an acceptable number of control points was used. For the external section of the turbine blade, 8 points in the U and 5 points in the V direction were generated. In the case of the internal section, 8 points were created in the U direction and 6 in the V direction. Also, it is important to mention that the control net of the external surface was modified in order to obtain a better match with the mesh surface.

Once the process was finished a solid body of the turbine blade is able to be exported into an *iges file for CAE analysis or into a .stl file for the generation of a rapid prototype of the work piece. Figure 13 shows the solid CAD model.
RESULTS AND DISCUSSION

Due to the scattering on the CT measurements, points on the section of the inner blade where not showed. In order to reduce the scattering of the CT scans two approaches were taken.

The first approach was through the development of a second filter for the scans. Here, a sheet aluminum box of 1mm in thickness was used. The piece was putted inside of the box so the box could be used as a second filter for the x-ray of the CT scanner.

The second approach was based in the surface approximation procedure. Here two steps were taken: the first one consisted in the use of a “rough” surface characterization in order to be able to detect some errors in the procedure. After this, the material of the piece was selected as a Region of Interest (ROI) and a second surface determination was carried on. This helped to reduce some of the errors generated during the CT procedure.

Although the scattering was greatly reduced through the use of the metal box and the 2-stages surface determination procedure, the use of the data of the optical scanner in order to develop the reconstructed 3D model was necessary. Therefore, using CT data for the internal cooling system and optical scanning data for the external cooling system, only one model was generated.

Due to this scattering, the surface characterization procedure described before did not allow a full surface regeneration, especially on the section of the inner blade, and therefore the data was unusable. Figure 14 shows the improvement on the quality of the scans by the use of the metal box.

![Figure 14. Effect of x-ray scattering in scans with no aluminum box (left, top and bottom) and with aluminum box (right, top and bottom).](image1)

During the RE procedure, a wall thickness analysis was developed in from the CT data in order to estimate the thickness on the surface blade. The results are showed in the histogram of Figure 15. Here it can be seen that the most frequent values of the part thickness are in a range from 50μm to 0.2mm.

![Figure 15. Thickness distribution through the work piece.](image2)

However, most of these values were found to be located in the zone of the fir tree as an internal porosity, as well as external cavities. The areas of the porosity of the material are circled in red in Figure 16. The top section of the figure shows a frontal look of the turbine blade, while the lower section of the image shows the view from the outer blade section. This can be attributable to the scattering of the x-ray during the scanning procedure or even during the surface determination procedure.

![Figure 16. Porosity presented in CT scans. Top: Frontal view. Bottom: Outer blade.](image3)

After the study of the CT scans was performed, another study of the final CAD model was developed. In order to account for the deviation of the final reconstructed 3D model, a comparison was made between the model and the mesh used as a base.

During the Re procedure there are two steps of the procedure where a loss of accuracy can of the raw 3D data can be generated. The first of them is during the editing procedure of the original 3D data (i.e. atypical data elimination, surface smoothing operations, polygon decimation). The second stage of the procedure where an accuracy loss can be generated is during the generation of the CAD solid.

In order to reduce this accuracy loss, the analysis software keeps the original location of the 3D data points and...
calculates the deviation between the original point and the point generated after the edition procedures. Such deviation is mapped in order to track the deviations generated during the generation of the 3D model [22]. The results are showed in Figure 17.

Here can be seen that most of the areas of the model have a deviation within a range of -/+50 μm. The areas with the biggest deviation present values of +25mm especially in the leading edge of the piece. This can be attributed to the manipulation of the control points of the NURBS surfaces during the reconstruction procedure.

![Figure 17. Deviation of the reconstructed model from the mesh.](image)

Lower sporadic with considerable deviations can be seen in the lower area of the piece, showed with yellow (+80μm) and blue (-80μm). Those deviations can be attributed to imperfections in the original work piece, since the reconstructed CAD model can be considered as “nominal”.

### CONCLUSIONS

The current work presented a RE methodology of freeform surfaces capable of accounting the internal section of a turbine blade without the need of destroying the piece. The total time for the application of the methodology was of 45 work hours from the first scan up to the final reconstructed 3D model. This represents 1/3 of the time used for the generation of 3D models from blueprints.

It can be assumed that most of the internal porosity of the work piece can be attributed to errors in the CT scanning, which were due to the material of the piece as well of its shape. Most of these issues can be classified as scattering of the x-ray in the scanning procedure, which has a subsequent impact on the surface determination stage.

Up to this point, the present methodology is not suitable for high tolerance parts, such as those used in aerospace industry, because of the scanning errors caused by the scattering of the x-rays due to the form and material of the original work piece.

In order to address these issues several suggestions on further research and development can be proposed, especially in the area of computerized tomography (CT):

- Effect of “super alloys” in the scattering of CT measurements.
- Impact of complex shapes on CT scanning.
- Development of methodologies for the assessment of the uncertainty of measurements with optical metrology systems.
- Development of methodologies for the assessment of the uncertainty in the inner sections of the work pieces.
- Optimization methodologies for the surface determination procedures of the CT scans.

### BIBLIOGRAPHY


