A reverse engineering methodology for nickel alloy turbine blades with internal features

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\section*{A B S T R A C T}

The scope of this work is to present a reverse engineering (RE) methodology for freeform surfaces, based on a case study of a turbine blade made of Inconel, including the reconstruction of its internal cooling system. The methodology uses an optical scanner and X-ray computed tomography (CT) equipment. Traceability of the measurements was obtained through the use of a Modular Freeform Gage (MFG). An uncertainty budget is presented for both measuring technologies and results show that the RE methodology presented is promising when comparing uncertainty values against common industrial tolerances.

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\section*{Introduction}

In order to face the strong competition existing in the global scenario, the aerospace industry is nowadays reducing the number of large components through re-engineering of product, design and manufacturing processes. Such modifications range from changes in the available design data to changes in manufacturing hardware and software technology [1].

Reverse engineering (RE) is one of the methodologies for obtaining information of these components in order to improve them. RE of aerospace components plays a crucial role in reconstructing mathematical geometric models for FEM analysis, rapid prototyping and the re-engineering procedures [2,3].

This work focuses on the development and study of a RE methodology for an aerospace turbine blade made of a nickel super alloy. The blade is formed having surfaces with free form shapes. This kind of surfaces may be classified as complex geometrical features, which cannot be represented as a combination of planes, spheres, cylinders or other simple shapes [4].

Turbine blades are subjected to extreme working conditions where the temperature may be raised as high as 1500 °C, with high mechanical and thermal stresses. To overcome these conditions, turbine blades are designed with an internal cooling system made out of several veins. Cooling air at around 650 °C is extracted from the compressor and passes through 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 RE is focused on the accuracy of the scanning process or the development of reconstruction procedures for complex external surfaces [1–3, 7,8]. The present work aims to develop a high accuracy and reliable method to perform RE operations on complex freeform components, taking into consideration the internal features of the component.

The structure of this work starts with a brief explanation of the technologies used and 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 investigation are discussed and an evaluation of the uncertainty of the measurements obtained using three different measuring technologies is presented.

\section*{Reverse engineering technologies}

The main task of RE is the reconstruction of an object whose geometry is composed of a number of surfaces of different shapes. The basic process stages of RE are [9]:

\begin{itemize}
  \item Coordinate measurements.
  \item Surface approximation.
  \item Use of data for specific tasks.
\end{itemize}
The proposed methodology uses two different measuring technologies for measuring 3D coordinates onto the work piece surface. This section presents a small briefing of each technology used: optical scanning and X-ray computed tomography.

**Optical scanning**

Triangulation sensors in optical scanners have become frequently employed for dimensional metrology in a wide variety of industries that go from the automotive to the medical industry [10,11]. Compared to mechanical probing systems, e.g., a tactile coordinate measuring machine (CMM), optical methods often can acquire more data in less time, with the advantages of measuring parts without contacting them [10].

These kinds of technologies have been used in RE procedures, but the scanning result may not achieve a high accuracy and have a higher uncertainty when compared to tactile systems [12]. Another disadvantage of optical systems comes from the preparation required for measurements of reflective parts. Such preparation requires spraying parts, which affects the accuracy of the measurement.

In order to address these issues, the combination of optical measurements and tactile systems, even at different times and locations, can yield a highly accurate 3D representation of the physical object, while reducing the time required for the data acquisition process [8,13].

For this work, an optical system based on a triangulation sensor was used to scan the external surface of a work piece. In order to ensure the quality and traceability of the measurements, a tactile CMM was used.

**X-ray computed tomography**

X-ray computed tomography (CT) has recently become an accepted inspection tool for a large number of industrial applications. Using CT, the internal geometrical features of a work piece can be measured without destroying it, which makes it unique and in many cases preferable to commonly used tactile or optical systems [12–15]. However, there are several sources of error in CT measurements that may affect scan quality and measurement accuracy. These sources include work piece related interaction effects of X-ray radiation (i.e. work piece material), source power (voltage and current), work piece orientation, etc. An example of these sources of error is beam hardening, which refers to the fact that, as the X-ray beam moves through material, low energy photons (i.e. soft X-rays) are more frequently attenuated than high-energy photons, resulting in a non-linear relationship between penetration lengths and attenuation coefficients and, as a consequence, to image artefacts in CT images. Another example is scatter radiation caused by scattered photons inside the work piece, resulting in image contrast losses. A classical approach to reduce, e.g., beam hardening artefacts, is to place a thin plate of Cu or Al in between the X-ray source and the work piece to filter out soft X-rays and to perform CT measurements with only the hard spectrum of the entire photon energy spectrum [16].

For this work, a CT scan for the RE of the internal features of a work piece, in our case a turbine plate, was used. The uncertainty of the internal measurements was not determined with the CMM, since this would have required destroying the turbine plate.

**Methodology**

The proposed RE methodology is shown in Fig. 1. The procedure involves a reference fixture as a basis for the digitization and measuring procedures. The measurements are then carried out on an optical scanner, CT scanner and a CMM, respectively.

The CMM is used for the generation of reference measures of the part and in order to achieve traceability to the unit meter, using a
dedicated artefact, known as modular free form gage (MFG) [17]. The use of the MFG is explained further in this section.

After the measurements were made, a reconstruction of the 3D model can be performed through the use of NURBS surfaces (non-uniform rational B-splines) and an uncertainty evaluation can be performed for each measurement system. The uncertainty evaluation can be based on the extraction of several random 3D coordinate points from each of the measurements, utilizing the “bootstrap sampling” method [18,19]. The procedure is explained further in this section.

**Modular freeform gage**

The evaluation of measurement uncertainty, when inspecting complex tolerances, is a difficult but important task. When measuring freeform surfaces, complexity is increased by the measure itself. The general model described by the “Guide to the estimation of uncertainty in measurement” (GUM) [20] is seldom directly applicable to complex measurements processes, and more specific evaluation procedures have been developed [21].

One of the approaches is based on the international standard ISO 15530-3 [22]. In this experimental approach, measurements are carried out in the same way, but with calibrated work pieces or working standards of similar dimensions and geometry instead of unknown objects. The procedure and conditions of both the actual measurements and the uncertainty evaluation shall be the same.

An artefact and a methodology for the traceability of freeform measurements were developed, taking into consideration the requirements of ISO 15530-3 [23]. The concept, “Modular Free form Gauge”, is to simulate a freeform measurement procedure with the measurement of surfaces on regular objects, combined in a set up representing the shape of interest as well as possible. The artefact is composed of [17]:

- Well-calibrated objects with regular geometry (spheres, cylinders, cones, rings, etc.).
- Modular and stable fixturing equipment.
- Variable configuration.
- A “calibrated” CAD model.

**Fig. 2** shows the design, modelling and calibration process of the modular free form gage (MFG) and each of the points is explained [23]:

- **Design of a MFG configuration:** In this phase, the actual freeform object is analysed and a particular MFG configuration is chosen, taking into account the similarity requirements, the target calibration uncertainty and the practical limitations.
- **Calibration of single objects:** The single objects are calibrated in both form and dimensions.
- **Assembly of the MFG configuration:** The single objects are assembled.
- **Calibration of the relative position:** The relative position of the object is measured using the basic software of the CMM and its length measuring capability. The “position points” (centre of spheres, points in the axis of cylinders) are saved in a file.
- **CAD modelling of the MFG configuration:** The CAD system and the mathematical basis for modelling are the same as for the freeform object.

The dimensions from calibration certificates are used for CAD modelling of the single objects.

Measurements are then carried out in the same way as actual measurements on the MFG. The specific experimental procedure as well as the uncertainty contribution of the MFG is presented in the following sections.

**Bootstrap method**

For the uncertainty evaluation, a set of sample points was extracted from each of the scans. Given an original sample of size \( n \), a single “bootstrap sample” is obtained by \( n \) extraction with replacement from the original experimental sample. A proper number of bootstrap samples enables the estimation of relevant population parameters, provided that the original experimental sample is representative of the population under investigation. This method is known as “bootstrap sampling” and it is a numerical approach to evaluate the variability of statistical estimators, such as least square estimators of geometrical parameters [18,19].

Using this data, the uncertainty evaluation was carried out following an approach as described in ISO 14253-2 and ISO 15530-3 [22,24].

For the estimation of the reference uncertainty, the MFG methodology is used. **Table 1** explains the uncertainty evaluation strategy for the MFG. **Table 2** represents the uncertainty evaluation strategy for the CMM, used as a reference uncertainty. **Table 3**

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<table>
<thead>
<tr>
<th>Table 1</th>
<th>Uncertainty budget for the MFG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty component</td>
<td>Symbol</td>
</tr>
<tr>
<td>Calibration uncertainty of single objects</td>
<td>( u_{\Delta f} )</td>
</tr>
<tr>
<td>Uncertainty of the relative positions</td>
<td>( u_{\Delta p} )</td>
</tr>
<tr>
<td>( u_{\Delta u} = \sqrt{u_{\Delta f}^2 + u_{\Delta p}^2} )</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Uncertainty budget for CMM measurements.</th>
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</thead>
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<td>Uncertainty component</td>
<td>Symbol</td>
</tr>
<tr>
<td>MFG uncertainty</td>
<td>( u_{MFG} )</td>
</tr>
<tr>
<td>Repeatability</td>
<td>( u_{MCM} )</td>
</tr>
<tr>
<td>Temperature</td>
<td>( u_{t} )</td>
</tr>
<tr>
<td>( u_{MCM} = \sqrt{u_{MFG}^2 + u_{MCM}^2 + u_{t}^2} )</td>
<td></td>
</tr>
</tbody>
</table>
shows the uncertainty calculation strategy for the optical scanner and Table 4 shows the strategy for the CT scans.

**Experimental investigation**

**Reference system**

**Fig. 3** shows the “rear side” (left) and “front side” (right) of the turbine blade made of Inconel 718 with an internal cooling system that was used for this particular case study. The experimental procedure begins by obtaining a reference system through the development of a special fixture and using it for the digitization and measurement procedures. The reference system consists of three steel spheres of 10 mm in diameter glued on the part as shown in **Fig. 4**.

Gluing of the spheres directly on the blade was used in this investigation. More generally, reference spheres or other fiducial marks can be fixed on a separate mounting plate. The positions of the spheres were chosen by selecting a point of the blade that can function as a system origin and selecting a planar surface that can ensure one of the datum axes (i.e. the fixture or one edge of the fire tree). These spheres must remain in the same position through all of the measurements. The points of the surface on the spheres are used in the stl data to generate “nominal” virtual spheres in the 3D model. After this, the centre points of the spheres are used to generate a common datum plane and a common coordinate system for its use during the RE procedure.

**Optical scanner**

Six different scans were performed on the optical scanner: three for the rear blade of the turbine and three for the front blade side. A 3Shape optical scanner, model Q800, was used for these scans. The measuring procedure consists of the following steps:

- Preparation of the piece with a coat of water based scanning spray.
- Set up of the piece in the machine.
- Machine set up (automatically for a dark object, high laser intensity).
- Scan cylinder adaptation (automated scan).
- Scan program definition.
- Data noise reduction and point cloud alignment.

The scan procedures were carried with 6 scans of 60° each at three different angles of the work piece: 75°, 45° and 10°.

**Table 4** Uncertainty budget for measurements with the CT scanner.

<table>
<thead>
<tr>
<th>Uncertainty component</th>
<th>Symbol</th>
<th>Type</th>
<th>Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference uncertainty</td>
<td>$u_{REF}$</td>
<td>A</td>
<td>Reference uncertainty (CMM)</td>
</tr>
<tr>
<td>Repeatability</td>
<td>$u_{QRT}$</td>
<td>A</td>
<td>Bootstrap method</td>
</tr>
<tr>
<td>Temperature</td>
<td>$u_q$</td>
<td>B</td>
<td>U-shaped distribution</td>
</tr>
</tbody>
</table>

$U_q = k \sqrt{u_{REF}^2 + u_{QRT}^2 + u_q^2}$

After the scans were performed, a surface determination procedure followed.

Limited radiation energy and scatter radiation did not allow for a highly accurate reconstruction of object boundaries, especially inside the internal sections of the blade.

In order to reduce X-ray scatter intensities, the blade was placed inside a metal sheet box of 1 mm thickness for the CT scan. This box
served as a second filter for soft X-rays and scatter radiation and a slight improvement regarding the image quality was reported.

After the surface determination procedure was finished, an *stl file was exported from the CT software and the extraction of points for the uncertainty assessment, the generation of the reference system, and the data size reduction procedures were performed in the same way as for the optical scans.

Although image quality improvements through the use of the metal box were ascertained, the data of the optical scanner was still needed for a steady reconstruction of the outer object boundaries. Due to this, only one 3D model was generated, using data from the optical scanner for the external reconstruction of the turbine plate and CT data for the internal section.

For the surface generation procedure it is important to notice that *stl data is composed of surfaces made by polygons which are described in a purely numerical way, as opposed to 3D CAD models, which represent surfaces in an analytical way based on equations.

The RE software uses the numerical data of each of the polygons in order to construct analytical equations of “bilinear surface elements” (i.e. straight lines). Such bilinear elements are generated in the form of NURBS curves [25]. Once the entire surface is divided in bilinear elements, such elements are merged in order to generate closed solid surface.

For the reconstruction of surfaces in this work, 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.

The use of NURBS surfaces was necessary in areas where a freeform surface was located. This type of surface was created by using a control net based on points automatically extracted from the point cloud, as shown in Fig. 6. It is important to mention that in case of a great density of control points in the net, the freeform surface might not be suitable for the real surface, due to the several changes in the curvature of the NURBS. Also, the control net was modified in order to obtain a more accurate surface, as depicted in Fig. 6.

Once the process was finished a solid body of the turbine blade could be exported into an *iges for the generation of a rapid prototype of the part. Fig. 7 shows the solid CAD model.

**CMM**

The CMM was used to obtain reference measurements. Likewise, the CMM and the MFG were used for the determination of a reference uncertainty value that was combined with the uncertainty estimations of the optical and CT measurements as explained later.

One of the measurements performed with the optical scanner was used in order to extract two basic geometries from the front blade of the work piece, getting two cylinders of 34.2 mm and 17.4 mm in diameter. However, and for practical reasons, the dimensions were changed to be adapted to more standard measures, still following the similarity requirements of ISO 15530-3.

For the construction of the MFG, two calibrated cylinders of 35 mm and 20 mm were used. The cylinders are tilted in two different directions in order to represent the curvature of the turbine blade. The largest cylinder is used to represent the outer section of the turbine blade while the smaller one is used to represent the inner section.

The 35 mm cylinder is tilted at 1° from the bottom part in the frontal plane and at 14° from the left side in order to represent the frontal of the turbine blade, while the 20 mm cylinder is tilted at 1° from the bottom and at 12° from the left, to represent the back of the blade. Their centre axes do not intersect the origin of the coordinate system of the reference fixture, Fig. 8 shows the frontal plane of the MFG.

For the measurements of the turbine plate (work piece), as well as for the measurement of the MFG, a Zeiss OMC 850 tactile CMM was used. The temperature during the measurements was

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**Table 5**  
CT scan parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>220 kV</td>
</tr>
<tr>
<td>Integration time</td>
<td>1000 s</td>
</tr>
<tr>
<td>Detector matrix</td>
<td>1024 x 1024</td>
</tr>
<tr>
<td>Number of projections</td>
<td>800</td>
</tr>
<tr>
<td>Voxel size</td>
<td>51 x 51 x 51 μm</td>
</tr>
</tbody>
</table>

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Fig. 5. Set up for turbine blade in CT scanner.

Fig. 6. NURBS surface for the reconstruction of the blade section.

Fig. 7. Final reconstructed model of the turbine blade. Left: external surface. Right: internal cooling system.
between 20.0 °C and 20.5 °C. The measuring procedure for the work piece, as well as for the MFG was carried as follows.

- Fixture of the work piece onto the CMM.
- Alignment of the work piece (through the use of the reference spheres and the walls of the fixture in the MFG).
- Programming of the CMM.
- Coordinate measurements.

Alignment of the turbine plate was performed with the same plane-line-points strategy as the alignments were done in the optical and CT scans in order to have the same coordinate system.

For the measurements, 198 points were taken and four repetitions were made. The probing stylus was provided with four tip points, although only one of the tips was used to make the measurements in the y-direction as shown in Fig. 9. The radius of the probe sphere was 1.4989 mm. The same measuring configuration and procedure were used for both work piece and MFG.

Once the probe tip correction was performed automatically by the software GOM Inspect, using the measuring vector direction, a shell for each one of the data sets was generated in order to compare it against the different meshes generated using optical and CT measurement technologies.

The data of the measuring of the work piece was exported to an "stl" file and compared to the different meshes of the CT and optical measurements. The data of the MFG was used for the determination of a reference uncertainty, as explained in the previous section.

Results and discussion

First, the shells generated by the point measure on the tactile CMM of the front blade of the work piece are aligned against the meshes in the RE procedure (see Fig. 1). Fig. 10 shows a comparison between the meshes calculated using the CMM and the optical scanner (Fig. 10c) and using the CT scanner (Fig. 10d). Furthermore, two graphs of the empirical distribution for the deviation values of the optical scanner vs. the tactile CMM (Fig. 10a) and CT scanner vs. the tactile CMM (Fig. 10b) are presented. Measurements less of 10 µm are not achievable by neither the optical scanner nor the CT system, therefore deviations less than those values are showed in the graphs as ±0.00 mm.

As can be seen in the graphs, the optical scan data show maximum deviations of +70 µm and −70 µm in the freeform area when compared to the tactile CMM results. However, most of the deviation values in the region are in a range of ±20 µm.

In the case of the CT scan data the maximum deviation values are +80 µm and −180 µm with most of the deviation values in a range of ±60 µm. It is important to notice that a positive value of the deviation means that the scans are offset to the outside material boundary (excess material) when compared to the CMM values, while negative values indicate that the offset is to the inside of the mesh generated by the CMM.

It turned out that the CT scans are considerably less accurate in some local regions than the ones made by the optical scanner. It can also be concluded from the empirical distributions that the highest deviation values can be considered as punctual errors in case of the optical scanner, since most of the areas of the CMM mesh have a deviation inside of the distribution range of the empirical distribution (Fig. 10a). For the CT scans, the deviation values are distributed following the same trend as for the optical scan, as can be seen in the light blue areas of Fig. 10c (optical scanner) and Fig. 10d (CT scanner). The biggest deviations of CT scan data are located on the top edge of the turbine plate. This can be attributed to scatter radiation, which can cause a distortion of the edges of the work piece.

In order to evaluate the quality of each measurement, an uncertainty evaluation was performed for the optical and the CT measurements. Following the proposed uncertainty assessment based on the use of the MFG, the results for the uncertainty estimation of the MFG can be seen in Table 6.

Table 7 shows the reference measurements taken with the CMM.

Tables 8 and 9 show the results for the uncertainty estimation for the optical and the CT measurements, respectively. Estimations were made with a coverage factor k = 2, in order to obtain a 95% confidence level [26].

The uncertainty results show a considerably bigger uncertainty for the CT scanner. This is in agreement with the lower accuracy of the CT scanner compared to the optical scanner, showed by the empirical distributions in Fig. 10a and b.

At the same time, the uncertainty estimation shows the repeatability of the procedures as the most significant contribution of the uncertainty of the measurements. Here it is important to mention that one of the reasoning for the low repeatability of the CT measurements is that different materials were scanned. Since the CT scanner and threshold parameters were set to the high-density material (Inconel 718), distortion of the surfaces of the spheres (used for the uncertainty calculation) was present in the scans. These results are significantly greater than those reported in an international CT study, where average CT uncertainty laid in the range of 14–53 µm. However, peaks of uncertainty in the mention study were reported to be as high as 158 µm on pieces with regular geometry [27].

Although some distortion was located in the surface of the spheres, the study of the X-rays showed that some areas of the inner side of the turbine blade show distortions that visibly look like porosity in the area of the fit tree. This can be caused by limited X-ray energy and image artefacts in the CT scan, resulting in threshold and surface errors. The areas of the image disruptions of
the material are circled in red in Fig. 11. The image at the top of Fig. 11 shows a lateral view of the turbine blade, while the image at the bottom shows a front view of the blade.

The distortion of the spheres is of great concern since once they are polygonized in a stl file, they are used to generate the reference system that allows the rest of the RE procedure. For this reason, CT parameters must be set taking into great consideration the material of the spheres and avoiding surface distortion.

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 basis. For this, 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 [28]. The results are shown in Fig. 12. Most of the areas of the model have a deviation within a range of ±50 μm. The areas with the highest deviation present values of +0.25 mm in the leading edge of the blade. This can be attributed to the manipulation of the control points of the NURBS surfaces during the reconstruction.

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

For the inner section it is important to notice that the nominal diameter for cooling channels of this type of turbine blades is in the order of 0.85 mm [29]. An approximation for the tolerance of the cooling channels was prepared based on a literature review. The result shows an approximate tolerance of 37 μm, which is consistent with data obtained in the industry [30].

### Table 6
Uncertainty estimation for MFG (values in μm).

<table>
<thead>
<tr>
<th>Uncertainty component</th>
<th>Type</th>
<th>Estimation</th>
<th>Standard uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration uncertainty of single objects</td>
<td>B</td>
<td>Calibration certificates</td>
<td>0.9</td>
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<td>Uncertainty of the relative positions</td>
<td>A</td>
<td>CMM measurements</td>
<td>5.5</td>
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<td>Combined standard uncertainty</td>
<td></td>
<td></td>
<td>5.6</td>
</tr>
<tr>
<td>Expanded uncertainty (k=2), (U_{MFG})</td>
<td></td>
<td></td>
<td>11.2</td>
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### Table 7
Uncertainty estimation for CMM (values in μm).

<table>
<thead>
<tr>
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<td>A</td>
<td>MFG Uncertainty</td>
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<td>Repeatability</td>
<td>A</td>
<td>Repeated CMM</td>
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<td>Temperature</td>
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<td>U-shaped distribution</td>
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<tr>
<td>Combined standard uncertainty</td>
<td></td>
<td></td>
<td>8.9</td>
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<tr>
<td>Expanded uncertainty (k=2), (U_{CMM})</td>
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<td></td>
<td>17.9</td>
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### Table 8
Uncertainty estimation for optical scanner (values in μm).

<table>
<thead>
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<th>Type</th>
<th>Estimation</th>
<th>Standard uncertainty</th>
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<tr>
<td>Reference uncertainty</td>
<td>A</td>
<td>Reference uncertainty (CMM)</td>
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<td>A</td>
<td>Bootstrap method</td>
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<td>Temperature</td>
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### Table 9
Uncertainty estimation for CT scanner (values in μm).

<table>
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<th>Type</th>
<th>Estimation</th>
<th>Standard uncertainty</th>
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<td>119.2</td>
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</table>
optical scanner and the CT scanner are used. With the use of NURBS surfaces deviations in the final reconstructed model of ±50 μm are obtained when compared to the scan data. Certain areas of the 3D model present deviations up to 250 μm. This can be attributed to the manipulation of the NURBS surfaces used during the construction of the blade section, as well as imperfections of the work piece itself.

Even though CT technologies are already being used in dimensional metrology, the uncertainty values for each of the methods shows that is not recommendable to use a micro CT scanner with a X-ray tube having a maximum tube voltage of 225 kV for the geometrical reconstruction of the external surface, due to a considerable bigger expanded uncertainty (119.2 μm) and less accuracy when compared to the optical scanning (expanded uncertainty equal to 43.7 μm). Inconel steel is a high-density material and high X-ray energy is needed for an acceptable penetration. In order to improve repeatability and accuracy, a micro focus X-ray tube with a tube voltage of at least 300 kV in combination with a line detector could be beneficial.

It can be assumed that most of the presented internal porosity of the turbine plate can be attributed to errors in the CT scan due to material and shape dependent interaction effects of X-ray radiation. Most of these issues can be attributed to limited X-ray energy, scatter radiation, and beam hardening and its subsequent impact on the surface determination step.

The total time for the application of the methodology was 45 work hours from the first scan up to the final reconstructed 3D model, without taking in consideration the time used for the uncertainty evaluation. The methodology requires one third of the time used for the generation of 3D models from blueprints and represents also a viable option to generate 3D CAD data when blueprints or “nominal” 3D models are not available due to a poor documentation, as it is the case with the present turbine blade.

When comparing the results of the RE methodology with industrial tolerances for internal cooling veins this work presents a promising strategy for the digitization of aerospace components with internal features. In order to improve the quality of the results and address issues that might occur during the scanning procedure, several suggestions on further research and development can be proposed, especially in the area of X-ray computed tomography:

- Understanding of image artefact formation at scanning of “super alloys” (scatter radiation, beam hardening) and development of compensation methods, e.g. by consideration of pre-knowledge.
- Impact of complex shapes on CT scan quality.
- Development of methodologies for the (non-destructive) assessment of the measurement uncertainties of inner sections (structures) of work pieces.
- Optimization of methodologies for optimal surface determination procedures of CT scans.

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