CAD model update on as-built geometries with morphing technique: ITER winding pack

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Abstract. CAD and CAE model update on manufactured shapes is a key process in the industry 4.0, where design, manufacturing and maintenance are integrated elements. Digital Twin models, together with Reverse Engineering (RE) techniques, allow tracking components performances during production and verifying the compliance with design requirements during the component lifetime. The need to have RE processes with a small impact on the production is driving the development of these models towards numerical techniques with fast computing performances. In this context, morphing techniques, largely deployed in the field of CAE models update, represent a valuable alternative to conventional RE techniques, because of their reduced computational time and capability to preserve the initial topology of the model. In the work presented in this paper, Radial Basis Function morphing technique has been used for the update of ITER Winding Pack CAD model on scan data acquired from the manufactured component.

1. Introduction

The design and development of ITER follows a dedicated European roadmap which aims at realizing a commercial Fusion Power Plant [1]. From a technical point of view, the basic principle of ITER is essentially represented by the presence of strong magnetic fields (peak field around 12 T), which confine a certain mass of high temperature plasma (150 M°C) within a toroidal chamber. The superconductive magnet system, which is part of the tokamak machine, is composed by the Central Solenoid (CS), the Poloidal Field Coil (PFC) and the Toroidal Field Coil (TFC) (see figure 1) systems. The latter consists of 18 D-shape winding packs (WP) enclosed in SS316LN cases (TFCC), which
connects the system to the other components of the ITER machine while providing the structural integrity and isolation to the superconductors.

The verification of the geometric conformity of produced components with respect to models generated by Computer-Aided Design (CAD) tools is a fundamental step in the realization of mechanical systems. In a typical mass production process, the dimensional control is carried out on sampled individuals. However, this procedure is not suitable for ITER critical systems since each part constitutes a "first of a kind", requiring a specific control throughout its life cycle. Furthermore, when it concerns large components subjected to significant changes in geometry due to flexibility, the possibility of a digital geometric reconstruction is crucial.

The WP manufacturing starts from the conductor cable assembly. The conductor is formed by 1400 cables of superconducting Nb3Sn and Cu strands fitted inside a Stainless Steel (SS) cable of about 45 mm in diameter. After being heat-treated at 650 °C in an inert atmosphere, the 750 m of the conductor are bent into a double spiral trajectory and then fitted inside the radial plate, which is represented by an SS structure with grooves on both sides. The sub-assembly is afterward locked by SS cover plates, which are laser welded by three robots working simultaneously to form a Double Pancake (DP). After being wrapped in the insulating tape and impregnated with resin, the component is cured at high temperature. Seven double pancakes are after that stacked, electrically jointed, wrapped and finally electrically insulated with glass Kapton tape to form the WP. The component undergoes another impregnation cycle before being finalized [2]. Previously the delivery, a series of final tests are carried out, including dimensional checks. The optimization of the manufacturing process, in particular the curing and thermal cycles in the DP stacking, lead to the production of WPs with reduced volumes compared to the nominal geometry.

In the TFC assembly stages, a comparison with the as-built geometries of the sub-components is often needed and, therefore, the digital twin approach, which updates the dimensional state of the component over time without discarding the original geometry, results to be much more suitable to the present needs (MacDonald et al. (2017) [3]). As part of the generation of a digital twin model, high-quality metrological techniques are to be considered as fundamental tools. Blue light scans, photogrammetry and contact-based measurement systems are typically used to verify the deviation of the real product from the reference CAD geometry. In the final stage of the WP manufacturing, the scan of the as-built component is performed using laser scanning technology, which provides data with a measurement error of approximately ± 0.5 mm, even for large-volume components.

Compared to the generation of a new CAD model, the update of the pre-existing digital model on the measured data allows a considerable saving in terms of time.

In the aeronautical field, Biancolini and Cella (2019) [4] demonstrated the feasibility of the digital model update approach within a study, which deals with an update of the Computer-Aided Engineering (CAE) model of the RIBES wing onto the actual manufactured shape. Such an innovative
coupled use of a mesh morphing technique based on Radial Basis Function (RBF) (Biancolini et al. (2018) [5]) and high-performance computing (HPC) cloud-based modelling and simulation techniques in the core of the Experiment n. 12 of Cloudifacturing “Update of CAE models on actual manufactured shapes” (CAEUp) [6].

2. CAD update by RBF morphing technique

The RBF technique has been proven to be a reliable and flexible method to interpolate discrete values (loads, displacements, etc.) over a certain field (Biancolini et al. (2018)[7], Groth et al. (2019) [8], Biancolini et al. (2019) [9] and Groth et al. (2019) [10]). Before being used in the CAD update, the RBFs technique has been deployed in several other fields, including meshless Fracture Mechanic (FM) [11] and FEM results improvement [12]. In this section, a brief description of RBFs is given to introduce the morphing technique adopted in the following paragraphs. Dedicated textbooks provide a wider description of mathematical background on RBFs, along with their applications ([13], [14], [15]). In the early 60s, problems of multidimensional interpolation have been tackled with the introduction of RBFs (Davis (1963) [16]). From a series of $N$ scattered scalar values attributed to their respective points $x_k$ in the space $\mathbb{R}$ (called source points), an approximating smooth function can be constructed in the same space with the usage of an interpolator $s$. At a location $x$ its value is:

$$ s(x) = \sum_{i=1}^{N} \gamma_i \varphi \left( \| x - x_k \| \right) $$ (1)

Having the function available, a corresponding value can be retrieved in a different point from the source in the space of the function. The variable $\varphi$ is attributed to the radial function, a scalar function based on the Euclidean distance between the source and target points. $\gamma_i$ are weights of the radial interactions whose order is equal to the number of source points introduced. For the computation of the weights, a linear system of equations needs to be solved. Typical radial functions are collected in the table below (table 1), for $r = \| x - x_k \|$:

| RBF             | Column A (t)                     |
|-----------------|----------------------------------|
| Spline type (Rn)| $r^n$, n odd                     |
| Thin plate spline| $r^n \log(r)$, n even            |
| Multiquadric (MQ)| $\sqrt{1 + r^2}$               |
| Inverse multiquadric (IMQ)| $\frac{1}{\sqrt{1 + r^2}}$    |
| Inverse quadric (IQ)| $\frac{1}{1 + r^2}$            |
| Gaussian (GS)   | $e^{-r^2}$                       |

In CAD-update applications, cloud points are the entities involved in the morphing and RBFs have to handle a vector field of displacement. In this case, each component is interpolated as an independent scalar field:
\[
\begin{align*}
\begin{aligned}
s_x(x) &= \sum_{i=1}^{N} \gamma_i \varphi(||x - x_{s_i}||) + \beta_1 x + \beta_2 y + \beta_3 z \\
s_y(x) &= \sum_{i=1}^{N} \gamma_i \varphi(||x - x_{s_i}||) + \beta_1 y + \beta_2 x + \beta_3 z \\
s_z(x) &= \sum_{i=1}^{N} \gamma_i \varphi(||x - x_{s_i}||) + \beta_1 z + \beta_2 x + \beta_3 y \\
\end{aligned}
\end{align*}
\]

(2)

Metrology techniques usually provide the information needed in the form of cloud points from which triangular tessellated surfaces generate. The input STereo Lithography (STL) is the target of the morphing action. For the application, a cubic spline function \( \varphi(r) = |r|^3 \) is substituted in equation (1), giving the following formula:

\[
\begin{align*}
\begin{aligned}
s(x) &= \sum_{i=1}^{N} \gamma_i \left( \frac{1}{(x - x_{s_i})^2 + (y - y_{s_i})^2 + (z - z_{s_i})^2} \right)^{3/2} + h(x) \\
\end{aligned}
\end{align*}
\]

(3)

On-surface and off-surface points’ distribution contributes to the construction of the function \( s(x) \), representing the interpolating, implicit zero iso-surface. Respectively at the surface inward and outward, two off-surface points are generated for every on-surface point, at a prescribed distance along the normal direction. Offset distance should be small enough to prevent off-surface points from clashing in regions of the surface characterized by small radiuses of curvature. The projection onto the implicit surface is carried out by Newton’s iteration method. The gradient of the function \( s(x) \) is:

\[
\nabla s(x) = \left( \frac{\partial s(x)}{\partial x}, \frac{\partial s(x)}{\partial y}, \frac{\partial s(x)}{\partial z} \right)^T
\]

(4)

Where:

\[
\begin{align*}
\frac{\partial s(x)}{\partial x} &= 3 \sum_{i=1}^{N} \gamma_i \left( \frac{1}{(x - x_{s_i})^2 + (y - y_{s_i})^2 + (z - z_{s_i})^2} \right)^{3/2} + \beta_1 \\
\frac{\partial s(x)}{\partial y} &= 3 \sum_{i=1}^{N} \gamma_i \left( \frac{1}{(x - x_{s_i})^2 + (y - y_{s_i})^2 + (z - z_{s_i})^2} \right)^{3/2} + \beta_2 \\
\frac{\partial s(x)}{\partial z} &= 3 \sum_{i=1}^{N} \gamma_i \left( \frac{1}{(x - x_{s_i})^2 + (y - y_{s_i})^2 + (z - z_{s_i})^2} \right)^{3/2} + \beta_3 \\
\end{align*}
\]

(5)

The projection of a point \( x \) onto the implicit surface can then be calculated iteratively by:

\[
x_{k+1} = x_k + \frac{s(x_k)}{\|\nabla s(x_k)\|} \nabla s(x_k)
\]

(6)

The above iteration runs until \( \|x_{k+1} - x_k\| \) is less than a given tolerance.

To improve the performances of the morpher, especially in the case of detailed and complex surfaces, a Partition of Unity (POU) methods Babuška and Melenk (1998) [17] and a fast iterative solver are deployed in the algorithm [15], allowing the reduction of the computational time from hours to minutes.

3. Problem description

The as-built WP point cloud is acquired with Leica Absolute Tracker AT901 and Leica T-Scan. With regards to the acquisition time and the component requirements in terms of quality of the measurements, three types of sampling areas are present in the final scan, each of them characterised by a different resolution and measurement uncertainty:
Table 2. Sampling areas resolution and related uncertainty

| Resolution [mm] | Total uncertainty at 2σ confidence interval [mm] |
|-----------------|--------------------------------------------------|
| 4               | 0.224                                            |
| 1               | 0.210                                            |
| 0.4             | 0.197                                            |

Considering the aforementioned properties, the generated STL file is composed of approximately 50M elements and 24 million points (see figure 2 on the left). The CAD model, on the other hand, is composed of 2 thousands tessellated surfaces (see figure 2 on the right).

![WP scan data (left) and baseline CAD model (right).](image)

**Figure 2.** WP scan data (left) and baseline CAD model (right).

![Model sample CAD geometry.](image)

**Figure 3.** Model sample CAD geometry.

A portion of the top end of the WP straight leg has been used in the test (see figure 3). The section transition and the complexity of the CAD surfaces make this portion a representative sample of the overall problem.

Due to the supporting configuration of the WP during the scan acquisition, some areas of the STL model do not present point data. To ease the solution of the RBF system in the morphing algorithm, fictitious points have been included in the model, respecting the curvature of the surrounding areas (see figure 4).
As shown in figure 5, the optimization of the DP stacking process led to the production of slimmer WPs. The deviations of the scan data from the nominal CAD show this phenomenon, with values of 2.5-4 mm on top and bottom surfaces in the Y direction, along which the DPs are stacked, while on the remaining faces smaller values are reported.

4. Workbench workflow and morphing setup
All operations concerning the study have been deployed in the ANSYS® Workbench™ platform. Specifically, three cells are present in the project schematic, as shown in figure 6:

4.1. Cell A, ANSYS® Mechanical® meshing tool
In this cell, a mesh is generated from the CAD initial geometry to obtain the input point data for the morphing routine. Nodes are arranged in sets employing the named selection feature, which will be used in the Cell C for the CAD update. Overall nodal spacing is 50 mm, with refined zones (2 mm spacing) in the fillet areas (see figure 7);
4.2. Cell B, ANSYS® Fluent® with RBF Morph™ add-on
The baseline point cloud generated in Cell A and the STL scan are the input data for this cell in which, as explained in the previous paragraph, the RBF algorithm generates the displacement field and applies it to the CAD point data, producing the morphed mesh for the CAD update. A different organization of the cloud points has been implemented in the morphing routine, where nodes are organized in four sets, representing the major surfaces of the WP sample, which are the most critical in the displacements field generation (see figure 8).

4.3. Cell C, ANSYS® FE Modeler
With its geometry synthesis algorithm, FE Modeler Cell offers a powerful tool to generate an updated CAD model without altering its initial topology (see figure 9). Morphed points are the input data for the CAD update algorithm, which uses the node partitioning introduced in Cell A to associate the surfaces to update to the correct set of morphed nodes.
5. Results
To highlight the differences from the initial configuration, the updated CAD geometry has been compared with the original scan data.

As shown in Figure 10, the resulting geometry adapted to the target scan data with high accuracy. Updated surfaces show a wavelike behavior, with differences from the target that vary from 0.05 mm to 0.5 mm, with a standard deviation of 0.2 mm.

![Figure 10. Deviations of the scan data from the updated CAD surfaces.](image)

To give an insight into the performances of the methodology, a comparison with a commercial RE software is proposed in table 3. The software makes usage of Non-Uniform Rational Basis Spline (NURBS) patching method (see figure 11) to reconstruct the CAD geometry directly from the scan data.

| Method               | CAD morphing          | NURBS patching         |
|----------------------|-----------------------|------------------------|
| StdDev               | 0.221                 | 0.087                  |
| Pts within +/-{1 * StdDev} | 1468351 (86.409%)     | 495300 (82.362%)       |
| Pts within +/-{2 * StdDev} | 1607505 (94.598%)     | 571248 (94.991%)       |
| Pts within +/-{3 * StdDev} | 1658204 (97.581%)     | 590666 (98.220%)       |
| Pts within +/-{4 * StdDev} | 1676160 (98.638%)     | 597068 (99.284%)       |
| Pts within +/-{5 * StdDev} | 1686775 (99.263%)     | 599472 (99.684%)       |
| Pts within +/-{6 * StdDev} | 1694032 (99.690%)     | 600477 (99.851%)       |

The methods produce comparable results, both in the standard deviation and in the shape of the Gaussian distribution.

It has to be remarked that, even if the NURBS patching method produces slightly better results than the morphing method, the process generate a different surface topology concerning the initial configuration.
6. Conclusions

In this paper a numerical procedure to adapt CAD models onto the actual manufactured shape of systems is described. The use of such procedure, based on the use of RBF mesh morphing, has been tested on a portion of ITER WP superconductive magnet. The study demonstrated the effectiveness of the proposed procedure with very limited deviations between the target scan data and morphed CAD configuration.

RBF mesh morphing confirmed to guarantee high accuracy and flexibility in tackling geometrical reconstruction problems providing the capability to significantly reduce the effort if compared to a model reconstruction procedure adopting RE software. Being linked to the initial CAD topology, the method is not suitable to as-built geometries in which deviation from the baseline configuration are related to the introduction of new features on the component (e.g. holes and pins). In the cases deviations due to the manufacturing process drive the CAD update, as in the big series production of components, the method offers short computational time and the possibility of automate the numerical process, making it a valuable alternative to commercial RE software. Future applications entail the possibility of the implementation of both methodologies in an RE workflow.

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