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A Digital Shadow cloud-based application to enhance quality control in manufacturing

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Abstract: In Industry 4.0 era, rapid changes to the global landscape of manufacturing are transforming industrial plants in increasingly more complex digital systems. One of the most impactful innovations generated in this context is the "Digital Twin", a digital copy of a physical asset, which is used to perform simulations, health predictions and life cycle management through the use of a synchronized data flow in the manufacturing plant. In this paper, an innovative approach is proposed in order to contribute to the current collection of applications of Digital Twin in manufacturing: a Digital Shadow cloud-based application to enhance quality control in the manufacturing process. In particular, the proposal comprises a Digital Shadow updated on high performance computing cloud infrastructure in order to recompute the performance prediction adopting a variation of the computer-aided engineering model shaped like the actual manufactured part. Thus, this methodology could make possible the qualification of even not compliant parts, and so shift the focus from the compliance to tolerance requirements to the compliance to usage requirements. The process is demonstrated adopting two examples: the structural assessment of the geometry of a shaft and the one of a simplified turbine blade. Moreover, the paper presents a discussion about the implications of the use of such a technology in the manufacturing context in terms of real-time implementation in a manufacturing line and lifecycle management.

Keywords: Digital Twin, quality control, Intelligent manufacturing systems, "As built" design, Life-cycle control, radial basis functions, Computer-aided engineering, mesh morphing.

1. INTRODUCTION

The global landscape of manufacturing is changing rapidly. In particular, industrial plants are becoming increasingly complex digital systems (Santolamazza et al. 2019), driven by the numerous technological innovations in the fields of ICT (Information and Communications Technology), electronics, data analysis and automation, developed in the context of the fourth industrial revolution (Dalenogare et al. 2018). To face the manufacturing trends in personalization, servitization, intelligence, and sustainability, different strategies have been proposed with the common goal of achieving a smart manufacturing environment (Tao et al. 2019c). Intelligence has attracted great attention from the manufacturing community and is, indeed, recognized as a key element for its future development for its ability to provide the flexibility necessary to remain competitive in a global market (Karkalos et al. 2019).

The paradigm of "Smart Manufacturing" has been described by the National Institute of Standards and Technology (NIST) as a "fully integrated, collaborative manufacturing system that responds in real time to meet changing demands and conditions in the factory, in the supply network and in customer needs" (Lu et al. 2016). It represents the integration of assets with sensors, computing platforms, communication technology, data intensive modeling, control, simulation and predictive engineering through the use of cyber-physical systems, internet of things, cloud computing and artificial intelligence (Kusiak 2018).

As a result of this ongoing research on the digitization of industrial plants, research in manufacturing has focused on the concept of Digital Twin (DT). This entity is the virtual counterpart of a physical component, product or system, which, exploiting a real-time synchronization of the sensed data coming from the field, includes more or less all information useful in the current and subsequent lifecycle phases thus making possible the enactment of smart decisions (Benedetti et al. 2019; Boschert and Rosen 2016; Negri et al. 2017).

In this context, Digital Twin can be exploited to further generate value from the information produced in the design

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phase to revolutionize the operational phases (Negri et al. 2017).

In this sense, the objective of the paper is to present an innovative implementation of a Digital Shadow (a specific subcategory of DT applications characterized by a data flow automated only from the physical object to the digital one (Kritzinger et al. 2018)) in manufacturing to support quality control operations, enabling the possibility of performing the qualification of even non-standard parts with a reduction of the time traditionally required for such operations. Indeed, traditionally, a virtual performance analysis would imply the use of a CAD (Computer-Aided Design) model completely developed from scratch using the measures acquired for the field.

The paper is structured as follows: Section 2 describes the background regarding the current applications of Digital Twin in manufacturing; Section 3 describes the research rationale and the proposal; Section 4 presents the main results of the first implementations of the proposed methodology; Section 5 reflects on the implications of the introduction of this approach in a manufacturing environment; finally, Section 6 proposes some concluding remarks.

2. BACKGROUND

Tao and al. described the Digital Twin as “a high-fidelity virtual model for each physical entity to provide deeper insights. The model can operate synchronously with the corresponding physical one and perform judgment, analysis, evaluation, and prediction, thus forming an intuitive mapping to the physical entity” (Tao et al. 2019d). This concept has been introduced first by Grieves in his product lifecycle management course (Tao et al. 2019b) and, then, expanded and consolidated in the aerospace field by NASA in 2010 (Shafto et al. 2010) when a Digital Twin was designed to be used to fly the actual vehicle’s future missions before its launch, to study the effects of various mission parameters, to validate fault and damage mitigation strategies, to conduct parametric studies as well as to mirror the actual flight of its flying twin in order to enable continuous predictions for it.

Furthermore, to highlight the possible degrees of data integration between the physical and digital entity, a further categorization has been proposed in the current scientific discussion (Kritzinger et al. 2018). Three different categories have been identified: Digital Model (digital and physical objects do not use an automated exchange of data), Digital Shadow (the automated data flow is one-way only, from the physical entity to the digital one) and Digital Twin (full automated and integrated data flow in both directions).

Since the first introduction of the concept, various possible applications have emerged (Negri et al. 2017; Kritzinger et al. 2018):

- support health analyses in order to improve maintenance activity and planning;
- digitally mirror the life of the physical entity in order to predict its behavior and future performances of the system and, therefore, to provide information continuity during its whole lifecycle;
- enable the virtual commissioning of the system;
- support decision making in order to optimize the system’s behavior during the design phase;
- layout plan through continuous production system evaluation;
- enhance production planning and control via decision support and automatic planning and execution.

While the industrial domains in which potential applications of the Digital Twin are being developed (e.g. electric power generation, automotive, oil and gas, healthcare and medicine, city management, agriculture and construction, etc.) are quite different, this technology can still be considered in an infant stage and it is envisioned that in future years it will penetrate into an increasing number of fields with the implementation of new applications (Tao et al. 2019a).

Indeed, a specific field which counts very few examples in terms of applications is the one of quality control. Moreover, the research in this direction has been focused almost entirely on the issue of geometry control and verification (Schleich et al. 2014; Yacob et al. 2019), instead of the one of performance control, which is the focus of this paper.

3. PROPOSAL

3.1 Rationale and Objective

Nowadays, different digital tools have been developed to assist the designer, from the early stages of conception of the product to the last stages of production. In comparison to previous technologies, they have the great advantage to allow a parametric analysis during the design phase, thus enabling the evaluation of how changes in variables of interest may impact specific indexes of the model. As a consequence, the tolerance interval on specific dimensions can be defined using parametric simulations: by varying the dimensions of the component at each step, the robustness of the product can be evaluated and operating conditions can be estimated accordingly. The advantage of this strategy is obvious, especially for large productions in which dimensional control is carried out on a sample of individuals: ensuring the compliance to the tolerance requirements guarantees the conformity of the product to the specifics in terms of quality.

However, this methodology cannot be applied to more critical cases, in which even small deviations from the ideal form may lead to a considerable deterioration in the performance. For these types of products, the simple verification of compliance with the prescribed tolerances may not be sufficient: an example of this issue is the case of turbine blades, which can occasionally present unexpectedly early fatigue damage, even in the absence of apparent problems; these phenomena are mainly to be attributed to stochastic form errors contained within machining tolerances (Srinivasan 1997).

Therefore, the opportunity to predict the behavior of the individual product in the situation of real employment constitutes an issue of great technical and economic impact for the manufacturer. Moreover, in other cases, it is sometimes necessary to evaluate the performance of a specific component during its entire employment. For these purposes, it would be useful to create an exact digital copy of the specific component, the "Digital Twin", to predict the component's real behavior throughout its entire lifecycle, starting with production and ending with its disposal, a concept also identified as "Digital Twin Instance (DTI)" by Grieves and Vickers (Grieves and Vickers 2017). In this specific applications, a crucial role is assumed not only by their ability to faithfully reproduce the real system but also by the speed with which they can be adapted and updated to the real reference (Schleich et al. 2017).

Thus, the creation of a Digital Twin becomes the most appropriate way to continuously monitor the performance of a component during the period of functionality. This leads to advantages not only to the efficiency of the system itself but also to the production process of the artifact under observation, thanks to the possibility of identifying and subsequently correct any manufacturing defects (Schützer et al. 2019).

In light of this, it is clear that in some cases the parametric approach for the performance analysis during the design stage is not able to always correctly anticipate the real situation. To solve this issue, the integration between the control systems and simulation environments can be extremely effective: through the use of measurements obtained from the real manufactured object, one can obtain a new digital model with the aim of determining the influence of defects on the functionality of the system in which it is inserted.

3.2 CAE^{Up} Experiment Design

Such an innovative approach has been the objective of the technical activities of the Experiment n.12 of the European project *CloudiFacturing* (i.e. Cloudification of Production Engineering for Predictive Digital Manufacturing) based on the use of advanced CAE (Computer-Aided Engineering) methodologies: "Update of CAE models on actual manufactured shapes" (CAE^{Up}), submitted by a consortium composed of two independent software vendors (RBF Morph s.r.l. and ANSYS Inc.), one value-added reseller (RINA Consulting S.p.A.) and one end user (CMS S.p.A.). *CloudiFacturing* has the aim to promote the optimization of production processes and producibility using high performance computing (HPC) cloud-based modeling and simulation.

In this context, the CAE^{Up} application has the objective to implement a cloudified numerical tool capable to rapidly project the nominal CAE model shape onto the digitalized representation of the real component through a mesh morphing technique based on the use of radial basis functions (RBF) (Biancolini and Cella 2019; Porziani et al. 2019; Pompa et al. 2020). In such a way, the performance of the part can be recomputed adopting a variation of the nominal CAE model shaped like the actual manufactured part in order to gain more accurate and reliable computational outputs and, furthermore, to be able to perform a qualification even for not compliant parts, with a clear benefit in terms of production costs.

In order to provide manufacturing industries with Digital Twins specific for each single component, a traditional approach would imply a reverse engineering operation performed on the geometry of specific components through modeling in the CAD environment, starting from real measures taken; the shape obtained would then be used for the virtual analysis of the performances.

Unlike the traditional approach, the CAE^{Up} approach plans to directly adapt the CAE model based on the nominal design geometry, on the digitized surface of the product. This allows to completely eliminate the reconstruction phase, with considerable savings in terms of time and with a reduced need for direct user intervention.

Figure 1 reports the schematic representation of the procedure for the Digital Twin generation following the proposed approach.

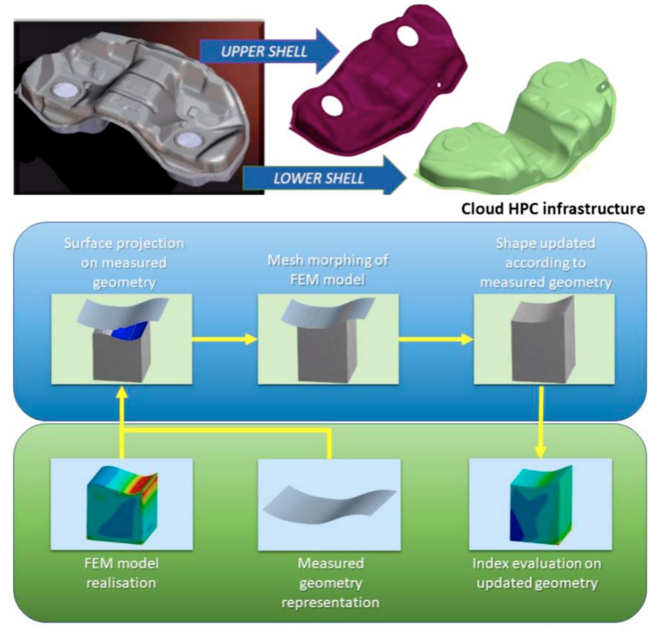

Fig. 1. Schematic representation of the procedure for the Digital Twin generation following the CAE^{Up} approach.

The steps of the approach are as follows:

1. at the local workstation a 3D scan acquires the manufactured part shape;
2. the FEM (Finite Element Method) model of the original designed configuration is transferred to the cloudified application together with the 3D scan of the real object. The FEM model is useful to

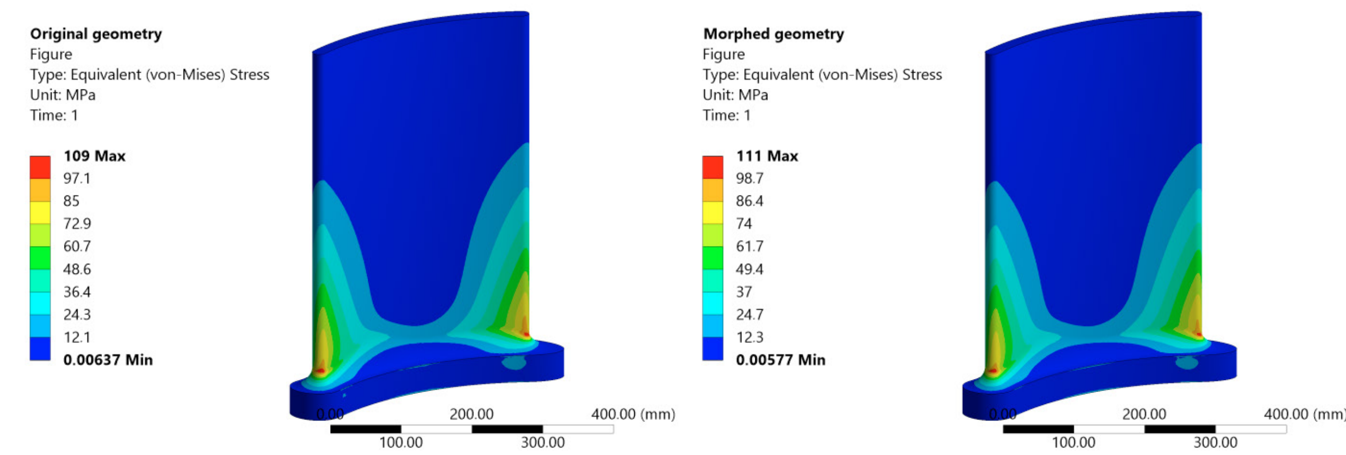

Fig. 2. Stress comparison between original geometry (a) and "actual" geometry (b) for the case of the turbine blade (Porziani et al. 2019).

interrogate the structural performance of the component;

3. the surfaces of the numerical model are updated according to the actual manufactured shape on the cloud platform;

4. the updated FEM model is transferred to the user's infrastructure in order to allow a new evaluation of the performance indexes and quantify the impact of the shape modifications occurred in the manufacturing process.

Since, at this stage, the proposed approach implies an automated unidirectional data flow, supporting the update of the digital copy of the real tested object to verify its structural adequacy and thus guarantee the passing of quality checks, the approach regards the implementation of a Digital Shadow of the manufactured objects.

4. EXPERIMENTAL APPLICATION

To test the proposed approach, following the work proposed in (Porziani et al. 2019), two examples of possible components were tested. The characteristics of each component were chosen in order to explore the potential and limits of the procedure in the case of different conformation and different conditions. The following cases were analyzed:

- a simple turbine blade, subject to summarized loads, with alterations at the base;
- a shaft, subjected to axial, bending and torsion loads.

To make up for the absence of actual manufactured objects in this first test of the procedure, shapes to be used as the "actual" 3D scanned components were generated by perturbing the baseline ones.

For the two cases, the perturbed geometries were used as inputs for the proposed approach together with the nominal CAE models.

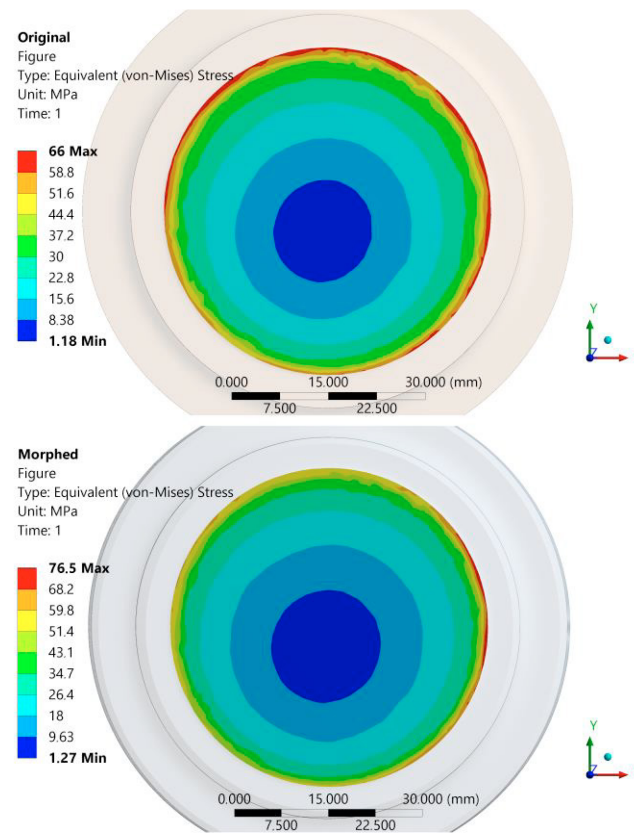

Fig. 3. Stress comparison between original geometry (a) and "actual" geometry (b) for the case of the shaft.

In regard to the case of the turbine blade, the original von Mises stress was computed to be about 109 MPa at the base. Instead, for the altered component, the stress was computed to be equal to 111 MPa, with an increase of approximately 2% (Figure 2).

In regard to the case of the shaft, the alteration of shape involved considerable increases in the recorded maximums. In particular, the sections at the junctions presented a minor redistribution of stress, with more evident local effects. Also, globally the value of the von Mises stress was definitely higher for the distorted geometry: compared to the 186 MPa stress value measured at the 20 mm diameter on the nominal model, the stress for the updated geometry was about 202 MPa, showing an increase of around 9%. The same behavior was also observed for the other regions with concentrated stresses: at the 25 mm diameter there was the highest variation, equal to 16%, from 66.0 MPa to 76.5 MPa (Figure 3).

5. FUTURE OUTLOOK

5.1 Implementation of the proposed approach on a local workstation

In this subsection, the direct implications according to the current results of the proposed approach are described. Indeed, the possibility of updating an existing CAE model in order to create a new one for an actual manufactured object could have huge benefits in an industrial context.

The first implication of this result is on the process of quality control. Using 3D scans, which are often already inside the industrial plant to conduct inspections of manufactured pieces, it would be possible to acquire the images for each produced object and use them as inputs for this approach. Each image would be sent on the cloud platform to perform the update of the nominal CAE model in order to test the compliance of the actual manufactured pieces with the set requirements. This would entail the possibility to perform a qualification of even not compliant objects. The obvious implication is the reduction of waste and, therefore, a reduction in production costs and waste material, achieving benefits both economical and from a sustainability point of view.

Indeed, as a result of the decrease of product waste, it has been estimated that, in the case of tanks (that are the manufactured components used in the *CloudiFacturing* Experiment), a reduction in the rate of individuals from 5% to 1% (which is a realistic estimation conducted with the manufacturer based on the results of the first applications of the CAE^{Up} approach) would lead to a saving of 484,000 €/year.

Moreover, the update of an original model would not require the need to generate a completely new CAE model and so would decrease the time needed to perform this activity.

As an ulterior consequence, this concept might also revolutionize contractual agreements with suppliers. Instead of having to guarantee the compliance of supplied parts and components within a strict tolerance in order to be able to guarantee the performances required, following this approach the supplier and the manufacturer might change the contractual terms and consider as faulty every and only the actual components that would not be actually suitable for the manufacturer's purposes.

5.2 Lifecycle Digital Twin

A future extension of the current approach is the possibility to create a Digital Twin of the real product that would be used even after the quality control phase. Lifecycle management is an aspect of uppermost importance in a manufacturing plant: a continuous awareness of the health state of a component is critical to operate the system to its best performance and thus to guarantee it the longest life and the minimum life cost possible (Santolamazza et al. 2018).

The new CAE model, representing the actual object, could become an asset connected to the real object in order to allow other operations and considerations such as maintenance control and execution. Indeed, as current maintenance methodologies for complex products are mostly based on similitude and heuristic considerations about the effects of operational and anomalous conditions on the structural health and performance of the product (Tao et al. 2018), with this methodology, as it has been already performed in the first phase of its utilization, the CAE model might be further updated during the whole life of the actual object in order to take into account the changes occurred (Biancolini et al. 2018; Biancolini and Valentini 2018; Groth et al. 2019). Therefore, the continuously updated model of a specific component of an assembly could become a valuable resource in terms of maintenance analysis. From a manufacturer's point of view, this application could also be considered as an adjunctive service installed in the product sold, thus adding further value to his offer to the market.

6. CONCLUSIONS

In this paper, an innovative procedure for quality control of manufacturing products, based on the update of the nominal CAE model onto the actual manufactured shape of the product, was presented. As this methodology could make possible the qualification of even not compliant parts, it fosters the shift of the focus from the compliance to tolerance requirements to the compliance to usage requirements.

In order to test its effectiveness, the use of such procedure was showcased using two case studies, consisting of a simplified version of a turbine blade and a shaft, and calculating the stress field of the baseline nominal configuration and the one of the morphed one, which reproduced the "actual" manufactured components.

Moreover, a discussion about the implications of this innovative approach was carried out, describing how this application would influence other manufacturing activities, such as maintenance, and how it would promote the efficacy of lifecycle management.

Further developments of this study will also see the test of the proposed approach on a real manufacturing line, in order to implement a full "Digital Twin", with automated bi-directional information flow, to support the quality control process and therefore assess the impact of this new approach on the productivity of the manufacturing plant.

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