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Towards the implementation of the Digital Twin in CMM inspection process: opportunities, challenges and proposals

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Abstract

The use of Digital Twin (DT) is adopted by manufacturers and have positive effects on the product manufacturing process. The aim of this paper is to define a Coordinate Measuring Machine (CMM) inspection DT model, based on inspection process digitalized functionalities, from one side, and Industry 4.0 opportunities (Digital thread, Big data, etc.), from the other side. A review about DT definition, is firstly presented. Secondly, we review related studies based on existing DT orientations and usages for CMM inspection. Thirdly, challenges related to the variation management are presented. Finally, a discussion about possible DT functionalities and opportunities is conducted then a CMM inspection DT model is presented.

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Keywords: Digital Twin; CMM; inspection; Model-based-defintion; Digital thread

1. Introduction

The inspection process, has a key role in manufacturing as a value-adding activity as well as a cost factor. Indeed, measurement data is a key to producing reliable information about the product [1]. There are different technologies which can assure inspection process.

Nomenclature

CAD	Computer Aided Design
CAIPP	Computer Aided Inspection Process Plan
MBD	Model Based Definition
DT	Digital Twin
CNC	Computer Numerical Control
DTh	Digital Thread
CMM	Coordinate Measurement Machine
IT	Information Technology
PMI	Product and Manufacturing Information
GD&T	Geometric Dimensions and Tolerances
CPS	Cyber Physical Systems
CAIS	computer-aided inspection system

In this paper we are interested in Coordinate measurement machine (CMM) inspection, which have been widely used as a means of evaluating product quality and controlling quality manufacturing processes. CMM are used, first, in assessing product quality and conformance with regard to original design intent, second, in providing feedback upstream. Usually, the measurement system is composed of four major phases, as mentioned in figure 1 (definition of dimensional and geometric specifications, unfolding of a measurement plan, measurement execution, and results analysis). These phases are digitalized

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and their related data are available through a digital thread (DTh), as well as the whole product development steps data.

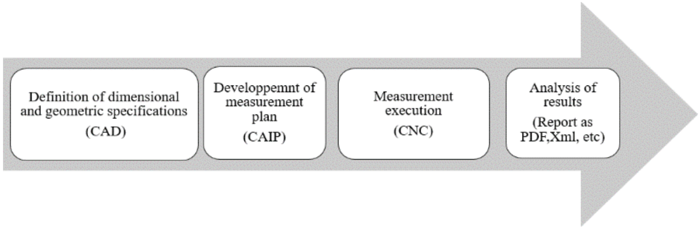

Fig. 1 The measurement system stages

The amount of data provided, through the digitalized process (DTh, Big data, Model-Based Definition (MBD) technology) enable, in a digital twin (DT) context, improving the manufacturing process by providing through a smart close-loop an optimized and unified inspection feedback (figure 2).

The objective, in this paper, is to propose a CMM inspection Digital Twin model, covering the inspection process functionalities and connected to the digital thread. To attempt this, CMM inspection functionalities must be determined throughout the inspection process. It is obvious that the digitalization of inspection process has greatly evolved. There are DT models for inspection process, which allow the inspection machine operator to visualize the impact of geometric variations. But several gaps and problems persist. In this research, firstly, we present an overview of DT definition. Secondly, we review related studies based on existing DT orientations and usages for CMM inspection. Thirdly, challenges related to the variation management in the implementation of DT are presented. Finally, a discussion about DT functionalities, opportunities and challenges is conducted. Then, a CMM inspection DT model is presented.

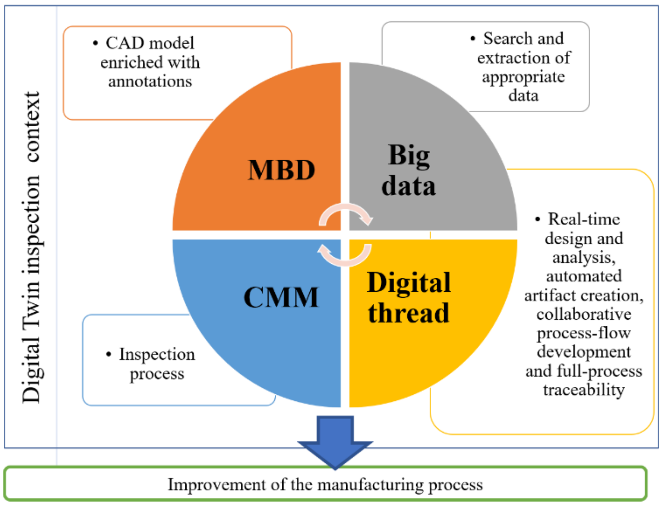

Fig.2 Digital Twin inspection elements for improving manufacturing process

2. Overview of DT history and evolution of its definitions

Today, we are living in a new digital era, based on the technologies of Internet of Things (IoT), which is technology that describes the network of physical objects. This technology can be used to collect and manage data directly from the physical products and processes in real-time. In this context, the concept of big data, which consists of valuable information assets having high volume, velocity and variety, is introduced to abstract useful information. This technological maturity leaded the re-adoption of the concept of Digital Twin introduced for the first time in 1969 by National Aeronautics and Space Administration (NASA)'s Apollo program, [2]. In fact, during these last 20 years, the concept of Digital Twin (DT)was the core of numerous researches, especially the last decade. However, up to today, there is not a standard definition of the concept of DT [3-4]. This variety is due to the employment of the concept on multiple use cases. In fact, many definitions of this concept were presented along this last decade. After the definition put forward by Professor Grieves in 2003, which consists that DT is only a virtual representation of a physical product at that time [5], NASA proposed officially, in 2010, the concept of DT as one of the top technical challenges in the report "Draft Modeling, Simulation, Information Technology & Processing Roadmap" [6].Then, according to them, it can be seen as virtual mirror of the physical ones, based from one side on the integration of multiple physics and scales and on the other side on the employment of dynamic sensor data and historical data from the product life cycle. This definition was improved by Glaessegen and Stargel, in 2012, where they defined Digital Twin as "an integrated multi-physics, multiscale, probabilistic simulation of a complex product, which functions to mirror the life of its corresponding twin". According to them Digital Twin consists of three parts: physical product, virtual product and the linkage between physical and virtual product [7]. Here, we start to talk about DT dimensions. Indeed, in 2014, Professor Grieves published the Whitepaper on DT, where he proposed its three-dimension structure (i.e., physical entity, virtual entity, and connection) and define its most valuable tools (i.e conceptualization, comparison, and collaboration). Based on these three dimensions, Rosen et al., in 2015, presented the DT as the model which can interact between autonomous system behaviours and the environment in the physical world [8]. From this, in 2018, Tao et al. added two other dimensions to the three proposed dimensions previously, which are DT data and services in order to satisfy the new demands for extending applications, embracing new Information Technology (IT), fusing physical and virtual data, generating intelligent services, and constructing ubiquitous connections [9]. Then, from a recent side, in 2019, Stark et al., developed the approach of "Digital Twin 8-dimension model" divided into two dimensions sides, the first one contains dimensions with focus on DT context and environment and the second one contains dimensions with focus on behaviour and capability richness [10]. They believe that the Digital Twin's decision-making and consistency processes must be based on a set of multimodal data from a variety of acquisition means. In the same way of finding DT dimensions, Van der Valk et al. 2020 found eight dimensions for DT (data link, processing data, conceptual elements, model accuracy, interface, synchronization, data input and time of creation) with 18 characteristics, after conducting a taxonomy of DTs based on the definitions given by Glaessgen and Stargel (2012), Grieves (2014) and Tao et al. (2018) [11]. Moreover, then DT dimensions, researchers work also on defining contexts on which the definition of DT depends. In fact, according to Zhang et al. (2020) [12], there are three contexts (i.e. the product, the production and the factory). For the product, the DT is an equivalent digital image that exists throughout the product life cycle [13]. For the production the DT is a digital representation that contains all the states and functions of a physical asset [14]. And for the factory the DT can be described as a digital copy of a real factory, which can be expanded and updated [16]. These DT definitions cited above, conduct researchers to affirm that DT can be a good solution for manufacturers to improve the manufacturing process based on products inspection results and being in coherence with the notion "minimum time" in industry. That' why researchers were focused in integrating DT in inspection process.

3. Digital CMM inspection process evolution and opportunities for DT

As mentioned in the introduction a classic CMM inspection process is based on 4 stages. Researchers, in this field, during these last 20 years, were focused on the digital evolution of these stages, in order to be in coherence with an evolutive digital industry. Hence, advanced technologies are used and can be opportunities for implementing a DT inspection model. In this section, we adopt the DT model with its eight dimensions presented by Stark et al. in 2019. These dimensions are listed below:

- 1.Integration breadth.
- 2.Connection mode.
- 3.Update frequency.
- 4.Product life cycle.
- 5.Cyber Physical Systems (CPS) intelligence.
- 6.The simulation capabilities.
- 7.The digital model richness.
- 8.The human interaction.

From the literature review, we aim to extract digitalized inspection process functionalities and opportunities, in relation with these dimensions throughout the inspection process stages, in order to propose a DT model for CMM inspection.

3.1. Digital Twin—The Digital Model—Digital Thread

Today we live a digital revolution based on advanced information technology such as big data, service-oriented architectures, networking and cloud computing, in all manufacturing processes towards a "Smart Factory" [1]. The inspection process, in the digital chain of industry 4.0, provides product information that allows, from one side, the verification and validation of conventional parameters used in the quality control derived from the comparison of the current model with the nominal model. From the other side, it gives information about the manufacturing conditions [16-17]. In order to help companies improving in a minimum time the geometric quality of their products, it is necessary to implement a DT inspection model. Such digitalization allows industries improving the product development process in earlier stages, although when quickly product change is demanded [18]. Hence, advanced machining processes demands improved techniques of metrology including high flexibility, universality and accuracy. The use of DT, seems to be a good solution, although it still in the initial stage in the inspection process. That's why the implementation DT in inspection process is studied within a whole process aiming at adopting the DT concept. Zhang and Zhu, (2019) proposed novel application framework of Digital Twin-driven product smart manufacturing system and analyzed its operation mechanism [19] (figure3). The inspection is also, underlined when it is necessary to implement DT in the assembly process [20-22]. In the same direction and based on Feature-based MBD Model retrieval, Zou et al. (2020). presented a Digital Twin model having a three-based layers structure, including geometric layer, data layer and document layer in order to make machining process optimization and quality prediction. The proposed model allows the expression of physical parts in digital space and the information correlation with theoretical processing features [23]. The designing information of a part in these works is obtained from a three-dimensional model with the model-based definition approach and transferred in bi-directional way through the digital thread within a closed loop strategy. Thereby, we can deduce that MBD, DTh and closed loop strategy, can be considered as opportunities for developing DT inspection model within a cyber space. That's why, we focus in the next section in the relation between Digital Twin, digital Model and digital Thread.

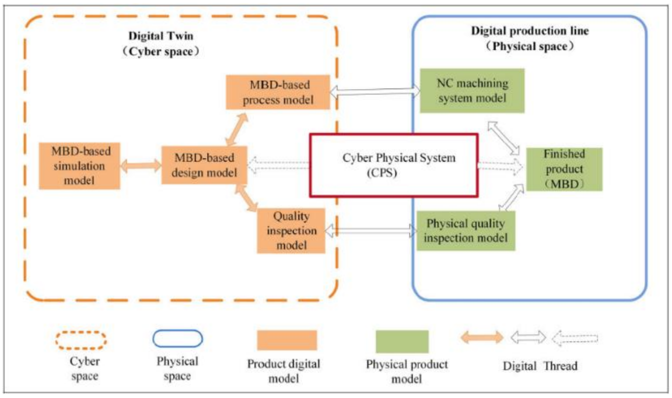

Fig.3 Application mode of closed-loop Digital Twin for fan blade smart manufacturing (Zhang and Zhu, 2019)

3.2. From Virtual CMM and inspection process simulation-towards DT

Based on definitions of DT cited above, The Digital model represent a relevant pillar which constitute DT. Researches during the last three decades worked on promoting new ways to define and communicate product design within the manufacturing process. Nowadays, modern Computer Aided Design (CAD) software can generate 3D CAD model associated to additional information. It is known as Product and Manufacturing Information (PMI). These PMI include geometric dimensions and tolerances (GD&T), material specifications, component lists, process specifications, and inspection requirements. It transmits non-geometric attributes in 3D CAD and collaborative production systems needed to manufacture components and assemblies of products. In focus with inspection process, from manually added to the CAD model features and to be in coherence with the notion "minimum time", PMI data, today, can be automatically extracted in order to identify features attached to the annotation and then generate the inspection plan. According to Herron (2013) [23], PMI conveys non-geometric attributes in 3D Computer Aided Design / Manufacturing / Inspection / Engineering (CAx) systems necessary for manufacturing product components. Recent advances in the design domain clearly converge towards the usage of 3D CAD models with annotations also known as model-based definition (MBD) [24], in the aim to define a unified information model that can be utilized throughout the product lifecycle and stored in a Product life cycle management system (PLM). According to Hedberg et al. (2016) [25], the digital thread (DTh) is defined as "the ensemble of data that enables the combination of MBD, manufacturing, and inspection". It enables real-time design and analysis, automated artifact creation, collaborative process-flow development and full-process traceability. Hence, we can deduce that DTh allows a real-time data transfer throughout the product lifecycle. Moreover, if this data is defined in an MBD approach it can offer a unified information model in this transfer. The unified digital model can be shared and use in a virtual CMM for simulation.

3.3. From Virtual CMM and inspection process simulation-towards DT

If we consider the first definition of DT proposed by grieves in 2003, where he considers that DT is a virtual representation of a physical product, we can categorize the virtual CMM as a DT model. The first time Virtual CMM was developed in 2012 for training novice operators by Zhao [26] where the measurement path is generated by a module which optimizes paths, considering points defined by a user. The inspection paths generated are represented only with a list of measuring points. Also, Wang et al. built a virtual CMM to control the machine based on recognized user hand motions by a gesture vision system [27]. Hu et al., in 2012, proposed a virtual CMM, where a user plans a measurement strategy. It performs measurements and evaluates the results without using a real machine [28]. The proposed methods can be used for training purposes. They present only static simulation of an inspection process plan execution. These methods don't provide any output instructions for reuse or the generation of new formalized plans. An improved inspection process planning simulation on a virtual CMM was proposed by Stojadinović, et al. (2020) [29], where they present an optimized and virtual measurement planning model. This model performs a simulation of the path and generates a report, that contains data about the motion of a measuring sensor and G-code for a real measurement process. The application, of the developed model, is limited to parts of medium and rough accuracy. They preview as future work the pairing of virtual and real on machine measurement system - towards the Digital Twin. Thereby, we can exploit the advanced functionalities of developed virtual CMMs to generate data motion of measuring report and G-code for real on-machine measurement. Then, this G-code will allow the execution of the measurement process and generate results.

3.4. Digital Twin inspection model

When the part measurement is performed by a CMM, dimensional data from the geometries of interest is collected, then analyzed through a computer-aided inspection system (CAIS) to determine errors related to GD&T. Results of that analysis are used, within a closed-loop, to feedback the process. According to Riaño et al.,2019 [30], a closed-loop inspection allows the implementation of strategies that lead the manufacturing systems to improve their efficiency and take better advantage of the resources involved in the manufactured part. Hence, they developed an integration strategy with a digital data model based on STEP-NC (Standard for the Exchange of Product model data - Numerical Control) for additive manufacturing (AM) closed-loop. The data models, in STEP-NC for the AM inspection, highlight the scenario of integrated feedback into the digital thread. At this stage, decision making about inspection strategy, based on captured knowledge can help improving the inspection process in real-time. In this way, some current works in the field of advanced inspection processes, are developed. In fact, researchers are focused on the preparation of the ground for inspection DT implantation. Anagnostakis et al., 2017 [31] proposed and demonstrated a novel digital engineering mixed reality paradigm, which has the potential to facilitate the rapid capture of implicit inspection knowledge and explicitly represent this in a formalized way. They affirmed that, if this proposal is automated, it can be used in a Digital Twin context to identify decision making and associated rationale and contribute to the formalization of CMM part programming techniques.

4. Digital Twin Vs Variation Management

The management of variations, is also a crucial operation in an advanced manufacture, especially for inspection process. Wärmefjord et al., (2020) [32] presented a survey to confirm the interest of Digital Twins in the area of Variation Management in mass-production, including inspection process as an important process in smart manufacture. They underlined that to achieve a complete and reliable Digital Twin, inspection data must be of high quality and linked to the 3D models. In their previous work, they mentioned that the Digital Twin concept can be used and ensure geometry assurance. Hence, they developed an inspection strategy to select what inspection data to extract and save from the manufacturing process that serve the Digital Twin [33]. In 2018, Schleich et al., (2018) treated the process of the online inspection Digital Twin system and they payed a particular focus on:

- Potentials and risks of increasingly available manufacturing data.
- The use of Digital Twins in geometrical variations management (Data quality).

For coordinate measuring machines (CMM) data, the right inspection points must be chosen, to maximize the information content in data. Where the relationship among the three-layer model is given for real-time communication which enables a real-time mapping between physical and virtual space, and the inspection process [34]. For this it is important to dispose of high-precision geometric representations, that's why Haag and Anderl (2019), developed a method for the topology-invariant modification of geometric product representations in order to be the core of Digital Twins [4]. This can allow modeling correctly a DT model. In this way, recently, Zheng et al., (2020) proposed a virtual modeling approach based on three-layers (i.e. Element, Behavior and Rule) for the physical environment modeling in a digital environment. Where the relationship among the three-layer model is given for real-time communication which enables a real-time mapping between physical and virtual space, and the process of the online inspection Digital Twin system [35]. The challenges, of geometric variations for implementing a DT inspection model, are the real-time management and the extraction of required data. This can be partially resolved based on capacities of DTh and Big data.

5. Proposition of CMM inspection DT model and announcement of opportunities for its implementation

As mentioned above, the aim of this paper is to propose a CMM inspection DT model. The literature review, realized in the previous sections, allowed us to extract the important functionalities required in the four stages of the inspection process (table1).

Table 1. Digitalized inspection process attempted functionalities.

Inspection stage	Required functionalities
CAD modelling	- Defining a unified information 3D CAD model with annotations [23-24]. - Updated CAD model [4], [34]
Inspection process plan	- Extracting inspection data [32-33] - High data quality [32-33] - Generate automatically Inspection process plans (CAIPP). - Reuse of plans [29] - Updated IPP [29] - Reducing cycle-time [18]
Inspection process	- Real time simulation [35] - Static simulation CMM [26] - Recognition of user hand motions [27] - Optimizing paths [26]. - High precision (choosing the right inspection points) [34] - Pairing of virtual and real inspection process [29]. - Inspection strategy based on captured knowledge [31].
Inspection results	- Generating Report [29] - Evaluating the results [28] - Comparing results to nominal model [16-17] - Closed-loop strategy [30] - Decision making and associated rationale [31]

To develop CMM inspection DT model, we exploit the extracted functionalities, from one side, and the definition of DT proposed by stark et al. in 2019, that we consider as a complete one, from the other side. In fact, we adopt the DT model with its eight dimensions, to the inspection process and we enrich each dimension with its required inspection functionalities developed by scientific researchers (figure 4). This model is based on the industry 4.0 opportunities, such as the Digital Thread, Big Data, the Model-Based Definition approach and the closed loop strategy. The MBD concept can be a legal documentation for delivering product, allows shorten the cycle-time considerably and reduces the risk of error from data re-entry [25]. It also serves as the single data source [20] and unified representation. That's why, we consider in this proposal that the data exchange within the DT is based on MBD representation.

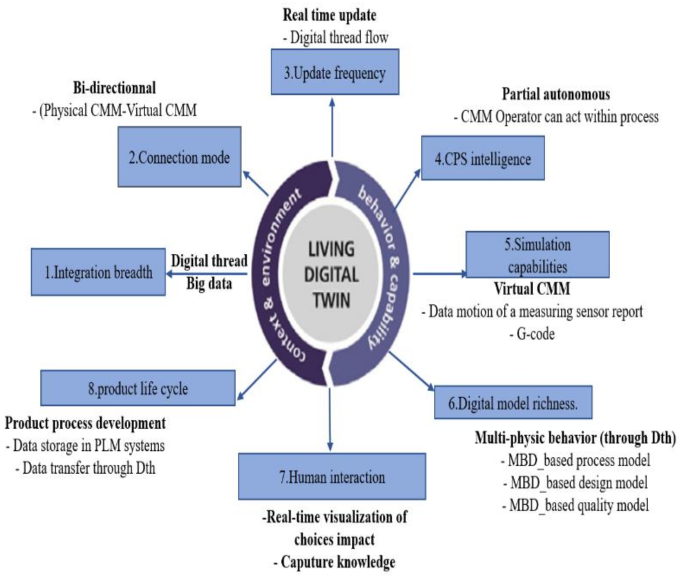

Fig. 4 The Digital Twin 8-dimension inspection model adopted from (stark et al., 2019)

6. Conclusion and perspectives

Digital industry, requires today the implementation a system that could manage easily the Big Bata through the digital thread, in the whole stages of the product development. Inspection step is a key of high-quality products. For this, we focused on exploiting advanced technologies such the Digital Twin. In this work, we develop firstly a literature review to define the concept of DT. In the second step, with focus to CMM inspection, we present related works in advanced CMM inspection field to extract, functionalities and opportunities which can respond to DT dimensions in order to implement it. Nevertheless, challenges due to geometric variations are also presented. Finally, based on the potential benefits of MBD, Big Data, Digital thread capacities and attempted digitalized inspection process functionalities, we present a CMM inspection Digital Twin model. The next contribution is to develop a unique and generic model which would integrate all extracted functionalities.

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