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Digital Twin in Metrology: Opportunities, Current Implementations and Research Challenges

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Abstract

Digital twin (DT) technology is now popular in several research and development applications, including also metrology. Measurements as a source of data play an important role not only in DT design, modelling and implementation, but digital twins of measurement systems can also be successfully used in many applications, for example to estimate measurement uncertainty. The digital twin method has a tremendous potential and many application possibilities in metrology, therefore in this paper some up-to-date research results in this area are presented and discussed, including some representative activities of National Metrology Institutes (NMIs).

Keywords: digital twin, quality assessment, uncertainty estimations, Central System for Metrology

1. Introduction

The term Digital Twin (DT) has been in circulation for several years [1, 2] to describe an integrated multiphysic, multiscale, probabilistic simulation of a system or object that uses the best available models, sensor information and input data to mirror and predict activities or performance over the life of its corresponding physical twin. More importantly, a typical DT is able to monitor the object and to share and update discrete data dynamically between the virtual and real systems or objects [3]. For this purpose, DT as a data-driven model can produce, for example, predictions which are directly equivalent to the quantity being measured.

Digital twin technology is nowadays extremely popular in several research and development applications. In addition, as mentioned by Fei et al. [39], the digital twin has progressed from theoretical research to pragmatic implementation, with modelling becoming a paramount constituent of the digital twin and a prerequisite for successful digital twin applications. Unfortunately, however, it is also still frequently considered an attractive lure or even a misunderstanding. As described by Wright and Davidson [1], DTs can be regarded as a right solution when the real object changes over time, which makes the initial model of the object invalid, and when measurement data correlated with this change can be captured. What is no less important, these changes could be undesirable, for instance wear or fatigue, or they could be neutral yet important for other reasons.

In light of the above, it is clear that measurements and measurement systems as a source of data play an important role in DT design, modelling and implementation. The use of DT as a modelling tool can also provide a significant support in metrology where, for example [4], digital twins of measurement systems are used to estimate their measurement uncertainty. Considering these aspects, there are available some promising new solutions and R&D applications of the DT technology, however at the same time there still exist many research challenges, especially keeping in mind the ongoing Industry 4.0 evolution and its requirements. For example, regarding DT applications in optical measurement systems [4], further research is required to include the influence of all error contributors such as temperature. The areas of DT applications are broad and still expanding in both research and development. There is no doubt that DT applications are slowly starting to be successfully used also in the field of metrology and measurements. The digital twin method has a tremendous potential and application possibilities in this field; therefore, in this paper are presented and discussed some up-to-date research results regarding quality inspection, quality assessment, measurement system uncertainty estimation etc. in which DTs were implemented.

2. Digital Twin-based systems in mechanical parts quality inspection

2.1. Virtual measurement systems for optimizing measurement planning

Measurement is a crucial process in advanced manufacturing industries to guarantee high quality products in compliance with their specifications. Many inspection systems rely on manual operations such as data import/export, geometric features inspection and inspection report generation. As the final inspection verifies the entire production process, it is crucial to ensure accuracy and reliability throughout the inspection process. Virtual representations of real measurement systems, DT-based measurement systems can improve the efficiency of physical ones [5-10].

Coordinate metrology is an important part of advanced manufacturing to achieve conformance of high quality products with design specifications. The first virtual coordinate metrology machine (VCMM) was developed in 2012. Methods proposed in early studies can be used for training purposes. Later works introduced new solutions providing optimized virtual measurement planning DT models for tactile and optical measurement techniques [5-12].

In [5,6] a virtual measurement system/digital inspection twin (DIT) was developed for the inspection of standard types of tolerances (e.g. concentricity, perpendicularity). The authors proposed a new approach to the CMM-based DIT, i.e. an off-line DIT based on the CMM by the control data list. The concept was described in [7]. The measurement system with the CMM was used as a physical twin, and a VCMM was generated after modelling and configuring using a specialized software package (PTC Creo). The VCMM made it possible to simulate a measurement process in order to check the collision and generate a measuring path for executing measurement on a physical part. The information flow was unidirectional and flowing from the virtual to the physical inspection system based on the CMM. In this way, a data format or a list of instructions for the physical machine and its movements per axes was provided. The VCMM was developed for inspection of the standard types of tolerances and family of prismatic parts, and turned out to be especially useful when planning the inspection parts with a large number of tolerances in industrial conditions. The method started with modeling the workpiece along with the specified tolerances, modeling the CMM components and clamping grips, and designing heads of probes in a CAD system. By setting up coordinate systems and selecting the appropriate kinematic connections of the machine CAD components, the VCMM was configured in the PTC Creo software system. The machine data chain, which was the focus of the work, ended with generating an .ncl (DMIS) code for a CMM model DEA-IOTA-2203. The obtained measurement data chain ended with the data generated by the CMM software.

The significance of effective and precise measurement of freeform surfaces is constantly growing. New DT-based solutions are proposed to increase measurement efficiency by using an automated robotic measurement system (RMS) [9, 10]. An original framework of a DT-based RMS for freeform surface parts which could improve the efficiency of the RMS was proposed by Tang et al. [9]. The procedure therein was analogous to that adopted in [6,7,8]. In accordance with the DT idea, the proposed framework of the DT-based RMS consisted of three parts, providing a practical solution to realize interconnection and integration between the digital and physical worlds. The physical space, i.e. the RMS, consisted of a cooperative robot, a structured light scanner, an electric turntable, and a special chuck for holding freeform surface objects. In a bridge connecting the physical space and the virtual space, i.e. the interaction space, the authors specified two layers: one was the data layer for handling heterogeneous multisource data (such as point cloud and image) and turning the collected data into information models based on the generally adopted OPC (Open Platform Communications) Unified Architecture standard, and the other was the platform layer which provided a toolchain of DT-based applications for modeling, simulation, visualization, learning, and inspection. Under this approach, virtual space tools were used for designing and developing DT-based functions for the RMS. The virtual space included [9]:

(1) the model layer which provided virtual units for the service layer and synchronized the state of virtual units to prepare a virtual environment for measurement applications; this layer stored virtual models, such as the geometric CAD models, the kinematic

model, the collision model, the learning model, and the inspection model;

(2) the service layer which provided core services for measurement tasks, i.e. visibility computation to compute the visible area of the target object as a key to the actual scanner acting simulations, accessibility analysis to determine accessibility of the viewpoint and kinematic solutions without any physical collision,

(3) the application layer which was designed to support measurement tasks such as viewpoint planning, path planning, 3-D reconstruction, and dimensional inspection. The aim of 3-D reconstruction was to reconstruct the point cloud model of the object; it also provided a model for dimensional and form tolerance inspection.

To test the proposed solution, case studies for viewpoint and path planning as well as 3-D reconstruction and dimensional inspection were presented and verified by simulations and experiments.

A measurement solution for freeform surfaces based on an optical micro-coordinate measurement machine (μCMM) using advanced focus variation offering advantages in terms of complete application, including the measurement strategy, was proposed by Zangl et al. [10]. Given that measurement planning, e.g. the number of measurements, their positions and probing directions, is essential for high-accurate and repeatable measurements, the applied therein μCMM software provided algorithms supporting the user in technology-based optimal measurement planning on CAD data by offering suggestions in terms of measurement method, probing direction or offline collision detection using a DT of the μCMM.

2.2. DT-based solutions supporting quality assessment and reliability

In CMM measurements, an effective measurement is one in which the probability of locating the greatest deviation is the highest with the smallest possible number of measurement points. The application of the DT of a product for effective CMM measurement strategy for parts containing freeform surfaces was proposed by Poniatowska [13]. The proposed approach to planning and performing coordinate measurements of form deviations of freeform surfaces processed under the same conditions involved using a surface CAD model built on the actual deviations and representing systematic deviations (Fig. 1). For this purpose, the random component had to be removed from the measurement data, and a surface model representing the reproducible deviations had to be determined. The data obtained from measurements made along a regular grid of points were used as a basis to create the model. To consider the variability of models between subsequently produced elements, the model of deterministic/systematic deviations should then be estimated based on a set of properly sampled surfaces by averaging the models built on data representing these surfaces. The averaged model could represent the characteristic patterns left by the machining process on surfaces with a specified variability between the surfaces. In effect, the deviation model superimposed on the nominal CAD model represented the product geometrical DT. Effective surface CMM measurements were planned locating the measurement points in the critical areas. Geometric deviations characterizing surfaces were obtained by measuring a definite small number of points in definite locations. The probability of locating the greatest deviation with the use of this solution was much higher when compared to the classical method.

Gohari et al. [14] developed a DT of an integrated inspection system (IIS), i.e. a system of measurement and analysis built directly into the manufacturing process, capable of conducting virtual sampling from a large set of point cloud captured from the workpiece on the production line. A virtual replica to work parallel to the IIS for the inspection of freeform and complex surfaces based on the metric of their geometric complexity was presented. An intelligently guided sampling was virtually conducted from a large dataset instead of the measurement sampling process when the sample points were randomly distributed on the measured surface. The presented method defined the location and number of the selected representative points. The reduction in the number of the sample points led to reduced inspection time and uncertainties in the evaluation of the substitute geometry and the estimation of the deviation zones. The method was tested experimentally, and the results showed the developed sampling strategy to be more effective in detecting extreme geometric deviations on the measured surfaces.

A method for inspecting the quality of product surfaces throughout the entire machining process based on an offline DT and artificial intelligence was developed by Ahmed and ElMaraghy [15]. To reduce average surface roughness, genetic algorithms were used to optimize machining settings. The proposed solution employed an offline DT model to calculate the average surface roughness during the machining process while also accounting for tool life, online acoustic signals, and cutting parameters (such as cutting velocity and feed rate). The offline DT was used to predict the Ra, simulate the cutting test, make decisions, and validate the adjusted

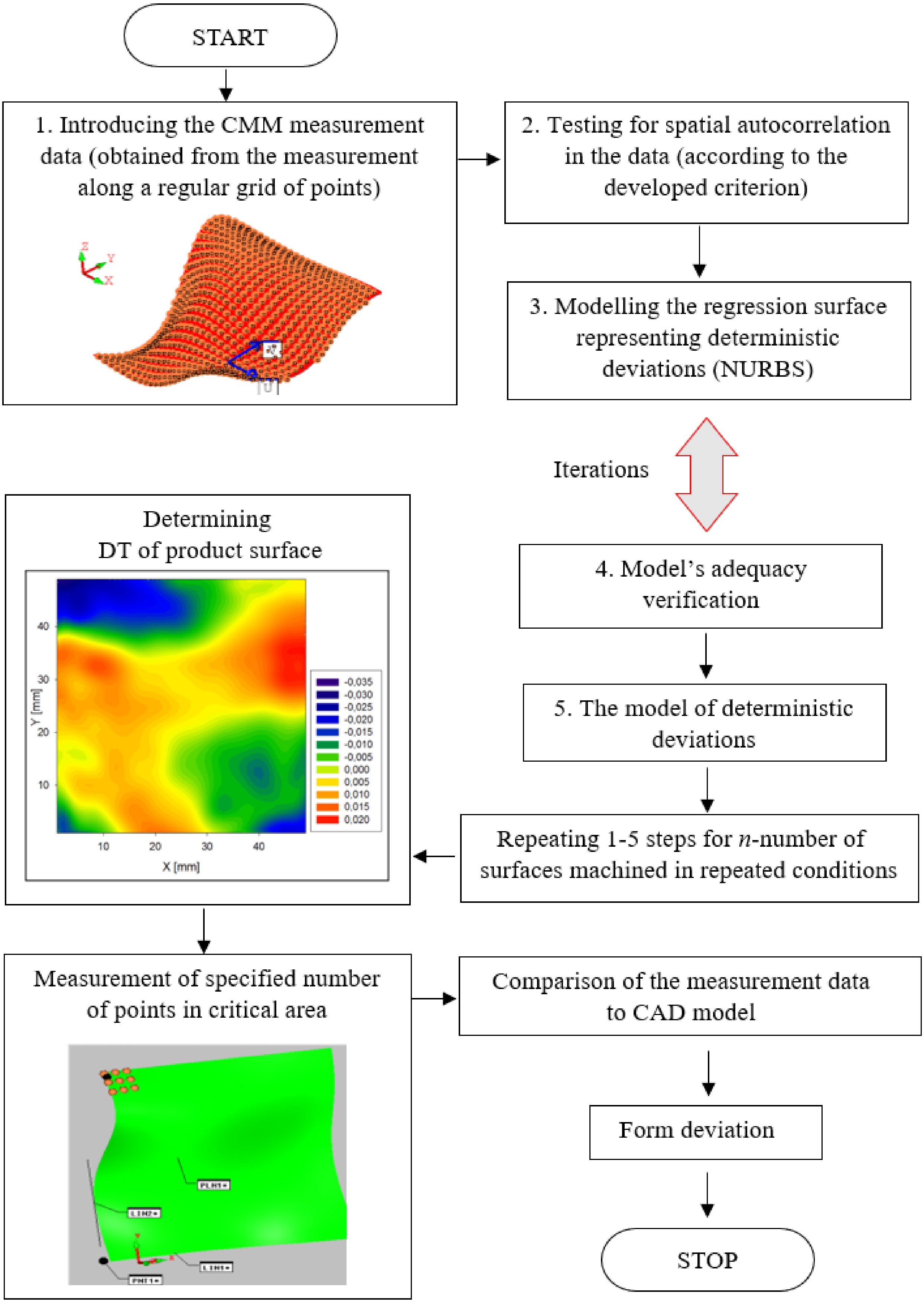


Figure 1 – Procedure of DT of product surface designing and applying for an effective measurement point distribution

parameters through the virtual machining process. After the machinist operated the CNC machine in the physical machining process for a specific machining task, the virtual machining process (the CNC machine) was driven for virtual machining by physical turning parameters. If the Ra values were normal, machining would continue until the task was completed. However, the machining parameters had to be corrected through the virtual machining process if the Ra values deviated from the norm. Actual machining data was used to test and validate the DT developed for the turning process. White light interferometry (Alicona InfniteFocus G5) was used to measure the average surface roughness of the surface. The authors verified the developed offline DT model experimentally, finding that the Ra value was stable and within the acceptable range. This was beneficial for improving the quality of the machined surface and reducing production costs.

The DT for geometry assurance concept depends on high quality input data describing geometrical features of individual parts, and the way in which this data should be collected, stored and utilized was described by Wärmefjord et al. [16]. A DT for product quality assurance was developed together with the product and the production system in early stages of the product realization process. Using inspection data from prototypes and test series, the inspection strategies during full production were further improved. When the full production started, the purpose of the DT shifted from analysis and development towards being a tool for real time optimization of geometrical quality. The work focused on the use of 3D scan data of parts and subassemblies in the manufacturing industry. If parts and resulting subassemblies with the parts assembled to each other were scanned, then the point clouds produced allowed for real time optimization of assembly processes and systems with higher product quality. The solution originally proposed in [17] is explained and refined in the present work.

Measurement systems with different types of sensors and data transmission technologies are now increasingly used to collect data throughout different stages of a product lifecycle, including product design, manufacturing, distribution, maintenance, and recycling. Digital Twin analytics can support effective data use to classify states, predict failures and enhance production efficiency. Data-based predictive maintenance with DT support has nowadays also become a new trend in prognostics and health management (PHM) for complex equipment. Its innovative approach to PHM, as described in [41], can help to achieve not only optimal maintenance action scheduling, but also process optimization with the use of the same data and measurement system, combining applied metrology and big data processing techniques with artificial intelligence and Digital Twin modelling.

2.3. Digital twins for measurement system uncertainty estimation

The correct assessment of compliance of product features with geometric specifications requires that the result be provided along with the measurement uncertainty. Methods for estimating uncertainty in coordinate measurement technique (CMT) are time-consuming and often require the use of special standards, multiple repetitions and extensive staff knowledge. Since the manufacturing Industry 4.0 needs short time and high quality inspection, the solution to this challenge is making a virtual measurement, i.e. creating a DT of its physical counterpart. The DT simulates the behavior of its physical counterpart, considering the specified error contributors such as the environment, measurement device, measurement strategy, evaluation strategy, and workpiece. The Monte Carlo (MC)-based approach for multiple virtual measurements makes it possible to determine measurement uncertainty [4, 18-24]. The use of virtual experiments and DT in metrology applications requires not only uncertainty estimation methods, but also reliable validation procedures to make them suitable as, for example, replacements or extensions of certified measurement devices.

A general structure of digital metrological twins as software for uncertainty estimation was proposed by Poroskun et al. [18]. The work provided a framework for MC-based uncertainty estimation software that could be used to guide the design and implementation for new measurement systems. The structure was taken from the VCMM. Digital twins of CMMs for the evaluation of measurement uncertainty based on the MC method have been extensively researched in recent years [4,18-24]. Different solutions in which the MC method was used for uncertainty estimation were obviously based on the same assumption. Under this assumption, to apply the software structure to specific projects in different fields of metrology, a supporting software library was created. The VCMM was analyzed and generalized, the reusable components of the VCMM were identified, extended and developed as a stand-alone software library. The library was designed to fulfil the specific requirements and implemented the GUM SI-compliant routines for uncertainty estimation.

Sładek and Gąska [19] developed the concept of a system enabling the determination of measurement uncertainty before the measurement is carried out on a specified real machine by considering experimentally determined error components, so that after analyzing potential measurement strategies, the one ensuring the highest accuracy could be selected. The study relate to a CMM equipped with a contact measurement head. The system consisted of two basic components: a CMM simulator and its virtual accuracy model. The simulator enabled the user to declare appropriate measurement tasks by indicating the position of measurement points and specifying the dimensions to be inspected. By using the simulator, it was possible to develop a measurement program and then implement it on the actual CMM. The other component of the prediction system, i.e. the virtual machine accuracy model, was developed at the Coordinate Metrology Laboratory of the Cracow University of Technology it comprised two modules. The first one was used for modelling errors generated by the machine’s kinematic system. It was based on experimentally determined distributions of residual errors, i.e. the errors which were not compensated for by the machine’s error correction system. Such errors were determined by the Laser-Tracer tracking system at selected points in the machine's measurement space. The other module was responsible for simulating measuring head errors. The module’s operation principle was based on the connection of head errors with the measuring point direction traverse. The data necessary for model preparation were acquired by measuring a spherical model in an appropriate number of evenly spaced points. This concept of VCMM and its operation were described in [21].

A study by Vlaeyen et al. [4] proposed a method for estimating measurement uncertainty in the DT of an optical measurement system consisting of a laser line scanner (LLS) mounted on a CMM. The development of a DT for uncertainty estimation for such complex system posed a significant challenge due to a high number of error contributors. Although the expression of a VCMM was derived from the state of the art [19-24], the virtual LLS was the original solution and included the measurement error as a function of the main error contributors, i.e. the scan depth, in-plane angle and out-of-plane angle. The error introduced by the LLS was determined considering the position of the laser source, the movement direction and the normal to the measured surface; consequently, adequate math equations were derived and presented. For the uncertainty estimation, 100 Monte Carlo simulations were generated. To validate the simulation results, two types of tests were performed on a set of ring gauges with different diameters – the first one was used to compare the uncertainty estimation obtained by the DT with the uncertainty of the repeated measurement experiments, and the other provided data for systematic error compensation. The validation confirmed that the DT of the optical system offered a reliable uncertainty estimation for all diameters involved. Uncertainty could be determined offline in order to shorten inspection times. This digital twin assumed stable measurement conditions and uniform surface characteristics. In further research, the authors intended to investigate the influence of all error contributors such as temperature and surface characteristics for objects with many different surfaces.

2.4. Digital twin approach to developing the freeform surface verification standard

In dimensional metrology, the calibration of measuring devices is highly important to ensure metrological traceability of coordinate measuring devices. Calibration standards equipped with basic geometric elements such as planes, spheres and cylinders are calibrated in laboratories, in the form of e.g. reference spheres, gauge blocks or step gauges, where legally controlled known measuring conditions, devices and procedures make it possible to estimate measurement uncertainty of these standards. In practical usage, a measuring device is calibrated and its capabilities are tested and verified by measuring the calibration standards according to the procedures defined by the ISO standards. However, the calibration standards equipped with primitive geometric elements are inadequate for measuring device calibration when it comes to freeform surface measurements. In [25] a new approach to developing calibration freeform standards with variable surface curvature and a known uncertainty was described. Inspired by previous experiences with manufactured and calibrated freeform standards designed on the basis of mathematical-geometrical descriptions, Sýkora et al. developed a Hyperbolic Paraboloid standard with dimensions of 300 mm × 300 mm × 160 mm (HP 300). The HP 300 verification standard consisted of a calibrated physical standard and a reference CAD model. The DT approach was applied to implement actual (manufactured) geometry into the reference CAD model. The actual geometry based on calibration/scanning point data (geometrical DT) was modelled as a B-spline surface to compensate for manufacturing errors with related uncertainty. The novelty of this approach was that the measurement result yielded by the HP 300 with its geometrical DT as the reference CAD model was not a manufacturing error, but an error of the measuring system. A practical application of the CAD-based measurement by the HP 300 on a tested/calibrated measuring device with respect to its geometrical DT was that the accuracy and freeform capabilities of the tested device could be determined by evaluating the values of individual point deviations measured in the workpiece coordinate system. A procedure for estimating the uncertainty of coordinate freeform measurement was also described in that study.

2.5. Research challenges and directions

The application of DT technology in the field of dimensional measurements remains a developing subject area, and there are still many challenges to be solved. The digital inspection process in the digital chain of Industry 4.0 provides information that allows the verification and validation of part quality control parameters obtained by comparing the actual model with the nominal model, as well as it provides information about the manufacturing process. The observed geometrical deviations of the part have various process-related sources and are inevitable throughout the whole part realization stages. The digital inspection process also provides the digital model representation of a physical part.

Under the idea of Industry 4.0, product realization processes are undergoing changes due to increasing digitalization. These changes are facilitated by cyber-physical production systems, the internet of things, big data cloud computing, and the use of DTs in geometry assurance [26]. Cyber-physical systems provide a link between the real and virtual worlds in manufacturing by data collection and sensor technologies [27]. The collected heterogeneous data involving/describing variations in manufacturing, assembly and joining processes which must be considered in the simulation models for realistic modelling and simulating include: (1) the geometric deviations of individual parts, (2) the variation propagation in an assembly, (3) the effect from joining in order to realize the concept of DT for geometry assurance and lead to geometrical variations management [16, 17, 26]. According to Schleich et al. [26], geometrical variations management can be understood as a set of activities related to controlling and minimization geometrical deviations and their effects on the product quality throughout the product life-cycle. The use of DT both poses challenges and shows great potential for new solutions in geometry assurance and geometrical variations management.

2.5.1. Interoperability/interconnection

One of the current challenges is the use of closed loop measurement result analysis to obtain feedback to support the production process. In the most recent literature, solutions using bi-directional transfer of designing information of the part through digital thread (DTh) within a closed loop strategy as opportunities for developing DT inspection model are proposed [27-29]. The key of such solutions is the usage of 3D CAD models associated with additional information, including GD&T, material specifications, component lists, process specifications, and inspection requirements. Such format of data conveys non-geometric attributes in 3D Computer Aided Design / Manufacturing / Inspection / Engineering (CAx) systems necessary for manufacturing product components. In most recent publications, 3D CAD models with annotations have been called as model-based definition (MBD). The DTh is defined as the ensemble of data that enables the combination of MBD, manufacturing, and inspection [29]. It allows a real-time data transfer through the product lifecycle, while the data is defined in an MBD format. The closed loop strategy makes it possible to implement strategies that lead to improved effectiveness in production systems.

When a part is measured using a CMM, dimensional data is collected from selected geometric features to determine dimensional deviations and tolerances (GD&T). To improve measurement efficiency, Riaño et al. [28] proposed a solution based on a closed loop strategy. They developed a concept of digital data model integration based on STEP-NC (Standard for the Exchange of Product model data – Numerical Control) for closed-loop incremental production. STEP-NC format data models used for dimensional assessment indicated the need for integrating feedback with DTh. The decision-making about CMM measurement strategy based on collected feedback could help improve the real-time accuracy control process. The whole product development data, including digitized measurement stages and their related data, can be available through DTh. In a DT context, all DTh-provided data help improve the manufacturing process. The proposal of a CMM inspection DT model, covering the inspection process functionalities and connection to DTh via the discussion of possible functionalities and opportunities, was presented by Gaha et al. [29]. The authors considered the bidirectional transfer of designing information about a part via DTh within a closed loop strategy as opportunities for developing DT inspection model. This solution could help improve the geometric quality of products within the shortest possible time. In connection with the above concept of closed loop strategy, the major challenge is to enhance the effectiveness of DT technology implementation by ensuring the interoperability between various types of manufacturing equipment and associated DTs, thereby exploiting the full potential of DTs in Industry 4.0 [2-32].

2.5.2. DT accuracy, validation and standardization

The effectiveness of DTs is inseparably linked to the need for their accuracy and standardization [30-34]. Due to more and more demanding accuracy requirements, DTs have to increase their accuracy on the one hand and adapt to new machine generations on the other. A study by Schnürer et al. [31] showed how machine learning tools could be utilized to synchronize DTs accurately and efficiently with real-world behavior by learning parameter values with measurement data while maintaining interpretable and robust analytical models. Khan et al. [34] emphasized the need for DT technology standardization and provided a standardized measure of the accuracy and reliability of a digital twin concerning its physical counterpart. This measure compared the similarity between a DT and its physical counterpart over time and space. They also underlined the importance of interoperability, real-time synchronization, accuracy, and fidelity in the standardization of DTs.

2.5.3. Data / geometrical data variations management

Large amounts of data acquired by heterogeneous scientific devices, sensor systems, measuring equipment, and experimental setups have to be processed and managed. An implementation solution for verifying complex products, including DTh, is based on process and data management for design and testing [16, 17, 26, 35-37]. A review of relevant literature reveals a research gap in the combination of approaches to research data management (RDM) and DTs. Recent publications have proposed new infrastructures for handling research data produced by various heterogeneous measurement devices and experimental setups. Lehman et al. [35] used an example of a photometer to show a complete integration scenario including every mandatory part of the RDM infrastructure. The end discussion revealed that DTs were a perfect companion for the realization of reliable and sustainable RDM to gain an added value. The study covered mandatory subparts of the overall RDM infrastructure, but single parts had to be examined in a much more fine-grained manner. Also, the authors indicated that a great deal of work had to be done regarding the integration of measuring devices and experimental setups. Lowenstein et al. [37] proposed a new concept of process and data management layer (DML). The DML could be an interface layer between model-based system engineering and simulation/test tools. They proposed extending the concept of CAE (computer-aided engineering) by including a testing process. According to their concept, digital threads had to link the design and the test process, from the specification requirements through the simulation and test processes to the final data produced by these processes. The input to the DML consisted of requirements and analysis requests, and the output was conformance to the requirements and analytics.

3. Integrating IoT and digital twins in metrology: the Central System for Metrology

The capabilities enabled by digital twins and digital metrology have the potential to enhance opportunities for data reuse and business improvement by creating new opportunities for product or service creation and uses for trustworthy data. They enable new development directions such as instant traceability, from measurement through sampling conditions and to global measurement standards or the creation of high-quality certified data markets. The benefits of introducing digital metrology for IoT measurements include [40]:

- more detailed knowledge about the uncertainty of measurement devices and their measurement results,
- data quality metrics are quantified as metadata,
- data quality traceability through the certification of origin, integrity and metrological quality of measurement data,
- higher market value of data thanks to the above reasons,
- cost savings in cases where calibration is a legal obligation, enabled by automatic data processing.

Launched as a pilot project in 2022, the Central System for Metrology (CSM - Centralny System Metrologiczny) at the Central Office of Measures joins the realms of metrology, digital twins and Internet of Things (IoT) technology. Serving as a hub, the platform is tasked with collecting, processing and analyzing data from a diverse array of measurement devices situated in varied settings. Outfitted with sensors and communication technology, each device relays real-time data to the central system. This data relating to measurements, operational status and environmental conditions provides a detailed snapshot of each device performance and condition. It serves as a prototype of digital twin technology in metrology, where each physical device is reflected through its digital counterpart, ensuring precise and real-time monitoring of its operations and functionalities. Currently, the prototype of CSM aids multiple laboratories by providing dashboards with environmental readings, which clearly demonstrates its utility and applicability in diverse metrological contexts.

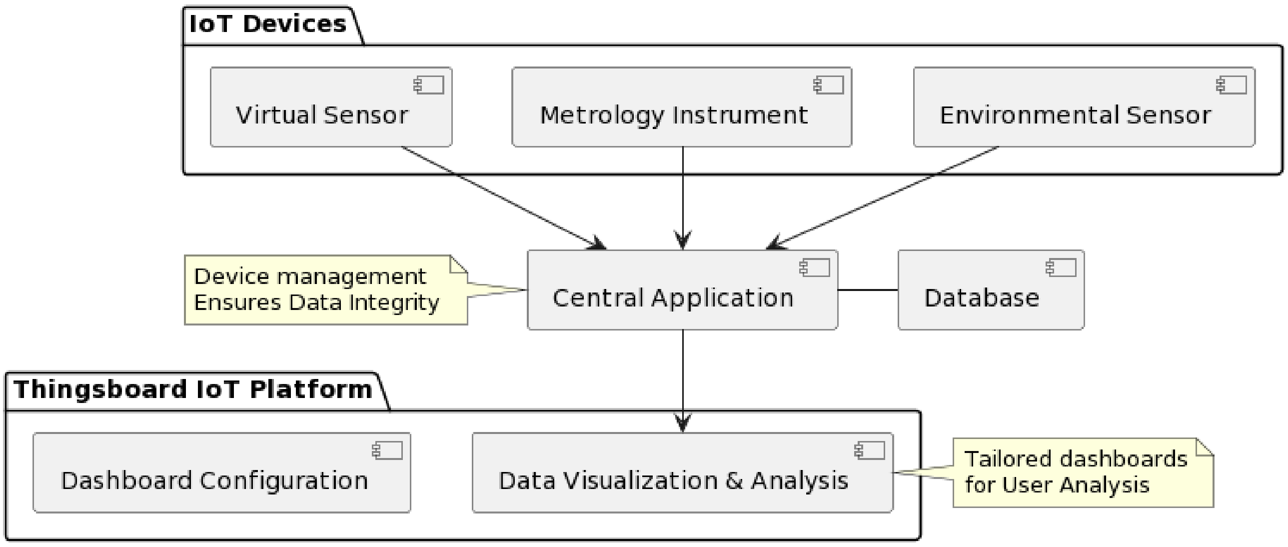
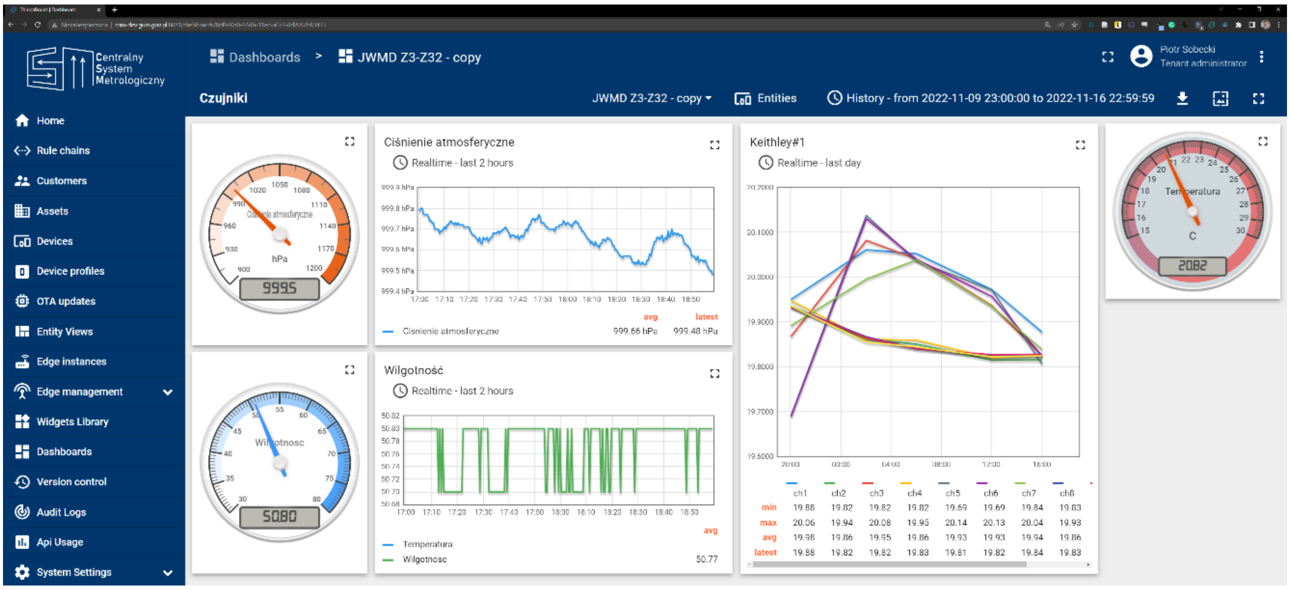


Figure 2 – CSM architecture diagram showing the integration of environmental, metrology and virtual sensors with IoT platform through a central application to ensure data integrity

The architecture under discussion is a network of IoT devices, comprising both environmental sensors and metrology instruments (Figure 2). This network is anchored by a central application designed to streamline the identification and management of devices. Each device within this network is uniquely identifiable, which enables precise tracking and data collection. Not only does the proposed architecture facilitate efficient device management, but it also ensures the integrity and reliability of gathered data, as well allows for its integration with other systems.

Complementary to this setup is an adapted Thingsboard IoT platform [38] which provides a user-friendly interface for data visualization and analysis, configurable for each laboratory (Figure 3). Dashboards are tailored to assimilate and display complex data streams from the IoT devices, offering users an intuitive means to monitor, analyze and derive insights from the data. The integration of the IoT platform in this context allows adaptability, catering to the specific needs of environmental sensing and metrological data management.



	ch1	ch2	ch3	ch4	ch5	ch6	ch7	ch8
min	19.88	19.82	19.82	19.82	19.69	19.69	19.84	19.83
max	20.06	19.94	20.08	19.95	20.14	20.13	20.04	19.93
avg	19.98	19.86	19.95	19.86	19.93	19.93	19.94	19.86
latest	19.88	19.82	19.82	19.83	19.81	19.82	19.84	19.83

Figure 3 – User interface of a CSM platform dashboard displaying real-time environmental readings for a selected laboratory

The platform is equipped with functionalities to enhance user interaction and operational efficiency. It facilitates the configuration of SMS and email alerts, enabling timely notifications based on specific criteria or thresholds. This is essential for immediate response to critical conditions or anomalies detected by the system, as well as for notifying metrologists that environmental variables in the laboratory are already stabilized for the measurements to follow. Additionally, the platform archives historical readings, providing a valuable repository of data for trend analysis and long-term monitoring. Furthermore, the platform supports integration of virtual sensors, potentially realized through specialized applications serving artificial intelligence models. These virtual sensors can simulate various conditions or predict outcomes, offering a layer of predictive capability to the system.

Crucial to this system is the digital twin aspect. Within the system, every physical measurement device is paired with a corresponding virtual model. These digital twins are dynamic, regularly updated with real-time data from their physical counterparts, which allows for detailed analyses. For instance, predictive maintenance can be streamlined through tailored AI virtual sensors to spot trends or irregularities that could signal impending failures or calibration discrepancies. Additionally, the digital twin framework streamlines remote diagnostics and problem-solving, thus reducing the need for in-person inspections and upkeep.

The Central System for Metrology described above can be extended with some features of the Distributed Ledger Technology (DLT) based concept to leverage digital metrology for IoT data and devices, and Digital Calibration Certificates (DCCs) offer a solution for describing, certifying, authenticating, and securing IoT data quality. With DCCs, measurement device (sensor) calibration information may be included as metadata alongside samples captured by the device [40]. This innovation proposed by Mustapää et al. [40] draws upon concepts from metrology and the Internet of Things, including Digital Twins, providing a compelling use case for digital metrology in cyberphysical systems. With the adoption of this concept, future data will be more usable across industries, as DCCs enhance trust in the accuracy, precision and timeliness of measurement data. According to its authors, this solution provides one means of validating metrological data for IoT devices, and the concepts are applicable outside of manufacturing and industrial applications. DCCs have the potential to change how we perceive the IoT-generated data, leading to a cross-industry revolution.

4. Conclusions

The digital twin and its physical counterpart operate on three levels [42]:

1. at the resource level – when creating a digital twin of a machine e.g. to predict the degree of wear of its key structural components, optimize the technological process or the measurement process carried out on this machine;
2. at the process level – when creating digital twins of all machines involved in the execution of a given process e.g. to optimize this process;
3. at the enterprise level – when creating digital twins of the business relations of a given business entity, including those with a distributed structure.

An important role in DT operation is played by real-time measurements and data processing using a suitable physical model that allows real-time simulation of a physical object or its structural components. As shown above, DT is beginning to play an increasingly important role in metrology and measurement. The data recorded during measurements not only provides the basis for mathematical modeling and the creation of a digital copy of a real object. The measurement process itself with its key aspects pertaining to measurement strategy, uncertainty, etc. has also become an area of increasingly effective applications of the digital twin technology, thus posing many research challenges and opening up new research directions.

National Metrology Institutions play an important role in this new and intriguing area of research by implementing activities aimed at integrating digitization, metrology, digital twins and Internet of Things (IoT) technology. By implementing innovative solutions such as virtual replicas of measuring devices and advanced IoT systems, these institutions help improve the accuracy and reliability of measurements. These activities are important not only for the development of new measurement techniques, but also for the optimization and monitoring of measurement processes in real time, which has a significant impact on the progress of various scientific and industrial fields. In addition to that, advanced technologies considerably support the work of metrologists by enabling more precise and faster measurements as well as relating them to historical values. The use of digital twins and IoT provides metrologists with access to detailed analyses and simulations, which considerably facilitates the identification and solution of potential measurement problems.

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