AMERICAN Journal of Engineering,
Mechanics and Architecture
Volume 3, Issue 12, 2025 ISSN (E): 2993-2637

Method and System for Constructing a Measuring Instrument Based on Digital Twin Technology

A. A. Yusupov
Associate Professor of the Department of Automation of Mechanical Engineering Process, Andijan State Technical Institute

Abstract: This article discusses an innovative approach to the design, manufacture, and operation of high-precision measuring instruments based on the concept of a digital twin. The proposed method enables the creation of a highly accurate virtual copy of a physical measuring device that integrates data on component geometric errors, assembly errors, static and dynamic system errors, and sensor characteristics. A multi-stage procedure for constructing such a digital twin is described, from design to calibration and operation. The architecture of the system, consisting of the physical subsystem of the device, its digital twin, and an integrated measurement management subsystem, is presented. A key advantage of this approach is the ability to predict measurement uncertainty, monitor instrument accuracy degradation in real time, optimize measurement trajectories on the virtual model, and, as a result, significantly improve the quality, reliability, and life cycle of measuring equipment. The method is illustrated using the example of constructing a coordinate measuring machine.

Keywords: digital twin, measuring instrument, precision metrology, measurement error, uncertainty, coordinate measuring machine (CMM), virtual model, calibration, geometric errors.

Introduction

Modern high-tech manufacturing, including aerospace, automotive, and microelectronics, places stringent demands on the accuracy and reliability of geometric inspection. The traditional lifecycle of precision measuring instruments (such as coordinate measuring machines, roundness gauges, and profilometers) includes sequential stages of design, component manufacturing, assembly, alignment, and periodic verification. The main drawbacks of this approach include weak communication between stages, the high dependence of final accuracy on the skills of personnel during assembly and setup, and the lack of systematic management and error prediction throughout the instrument's service life [1, 2].

Digital Twin technology offers a paradigm capable of revolutionizing this process. A digital twin is a virtual dynamic model of a physical object or system that simulates its behavior, is updated based on sensor data, and can be used for analysis, prediction, and optimization [3]. When applied to measuring equipment, a digital twin enables the creation of an accurate computer model of the device, accounting for all sources of error, opening up opportunities for end-to-end modeling of metrological characteristics.

The goal of this work is to develop and describe a comprehensive method and corresponding system for constructing a measuring instrument, in which the digital twin acts as an integral part linking the stages of design, production, calibration, and operation.

1. The current state of the research problem.

Existing methods for ensuring the accuracy of measuring instruments primarily focus on the control and compensation stages. Laser interferometers, electronic levels, and standard standards are used for alignment [4]. Methods for mathematical compensation of systematic errors are being developed, for example, using transformation matrices or polynomial models [5]. However, these methods are often disjointed: error models are constructed for an already assembled instrument and do not account for the contribution of individual component and assembly errors. CAD/CAE technologies are widely used at the design stage, but the resulting models are typically idealized and do not transform into a functioning digital twin linked to the physical object throughout its lifecycle [6].

Therefore, a pressing challenge is to create an end-to-end methodology where the virtual model evolves alongside the physical instrument, accumulating information about its real-world condition and providing intelligent measurement support.

2. Method for constructing a measuring device based on a digital twin.

The proposed method includes eight consecutive stages that form an iterative cycle of refining the digital model (Fig. 1).

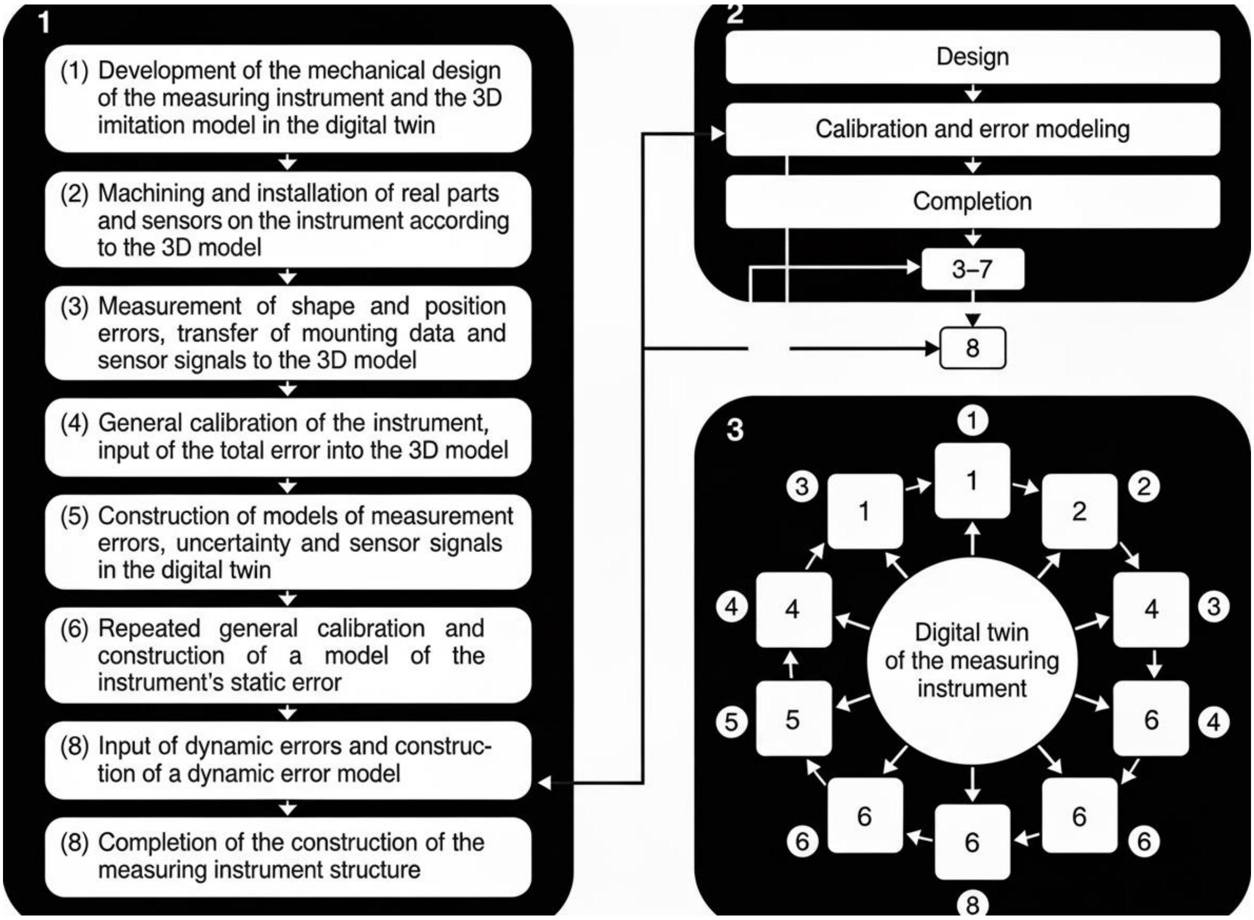

Fig. 1. Block diagram of the process of constructing a digital twin of a measuring device based on a three-dimensional simulation model and error calibration.

Figure 1 illustrates the end-to-end process of constructing a digital twin of a measuring instrument: from the virtual design of the mechanical structure and the creation of a 3D model to the operation of the digital copy in monitoring mode. In the first stage, the instrument design is developed based on the technical specifications and a parametric CAD model is generated, in which kinematic and strength calculations are performed. Physical components are then manufactured using this model, their actual geometric parameters are measured, and these are entered into the digital twin, ensuring the correspondence between the virtual and physical copies. After assembly, sensor installation and mounting errors are taken into account, a general machine calibration is performed with the generation of a systematic error map, and metamodels of measurement, uncertainty, and sensor signals are constructed in the digital twin environment. Static and dynamic error models are then refined based on repeated calibrations and motion tests. The completed digital twin is used during the operational phase to support the actual instrument: predicting accuracy, compensating for errors, and supporting decision-making during its use and upgrades. Using a digital twin during the design and operation of a measuring instrument enables the combined analysis of sensor data and simulation results, streamlining the calibration process and reducing the amount of physical experiments required to achieve the specified accuracy. This virtual model enables the assessment of measurement uncertainty in various operating modes and the early detection of instrument degradation trends, increasing the reliability and predictability of its operation.

3. System Architecture.

The system implements the proposed method and has a three-component architecture (Fig. 2):

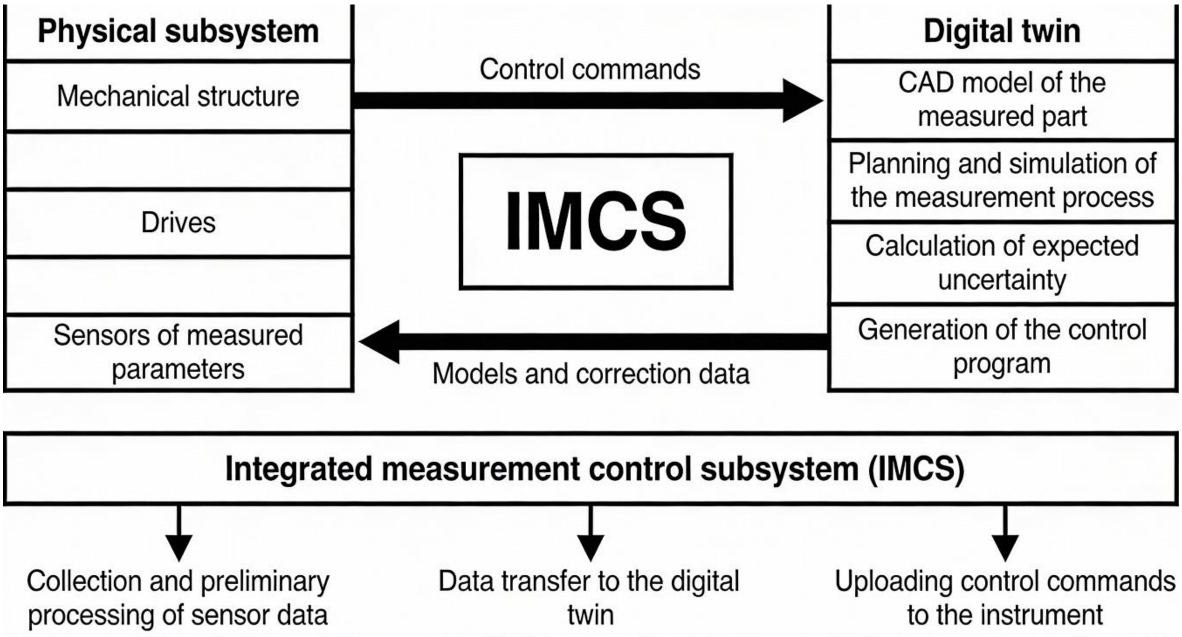

Fig. 2. Architecture of the measuring instrument system based on a digital twin.

The presented graphical diagram reflects the architecture of a measuring instrument system implementing the digital twin principle and formally describes the closed-loop interaction between physical and virtual components. The top level of the diagram identifies two dominant essential blocks: the physical subsystem, including the mechanical structure, actuators, and measuring sensors, and the digital twin, which is a virtual replica of the instrument preserving its geometric, kinematic, and metrological characteristics. The lower level houses the hardware and software suite of the integrated measurement control subsystem (IMCS), which provides the information and control link between them.

Bidirectional communication channels between the physical subsystem and the IMCS are interpreted as a flow of measurement information (downstream) and control actions (upstream), enabling real-time recording of the measuring instrument's state and closing the control loop based on the calculation results in the digital twin. Similarly, the two-way links between the control unit and the digital twin reflect the continuous synchronization of the virtual model with the physical object: telemetry data and calibration results used to update the mathematical models are received from the physical subsystem via the control unit, while optimized control programs adjusting motion parameters, sensor operating modes, and measurement strategies are transmitted from the digital twin to the control unit.

The internal structure of the digital twin block, presented as a list of functions, defines the functional decomposition of the virtual subsystem: the module for receiving the parameters of the measured part uses the CAD description of the object; the module for planning and simulating the measurement process checks trajectories for collisions and assesses surface accessibility; the block for calculating expected uncertainty generates a priori accuracy estimates taking into account the identified error models; and the control program generation module synthesizes a machine-readable measurement scenario for the physical subsystem. Thus, the diagram demonstrates the cyber-physical nature of the system: the digital twin is not a passive model, but functions as an active element of control and uncertainty assessment, forming the basis for adaptive metrological support throughout the entire life cycle of the measuring instrument.

4. Implementation Example: Coordinate Measuring Machine (CMM).

This demonstration examines the process of creating a digital twin for a three-axis measuring machine. During the design phase, a gantry structure is modeled in a CAD system, and components are selected. After manufacturing, the actual geometric deviations of the crosshead, X, Y, and Z-axis guides, and carriages are measured. The data is entered into the model (Fig. 3).

Feedback sensors are installed, and their rated accuracy and installation errors are entered into the sensor model of the digital twin. After assembly, the CMM is calibrated using a high-precision reference ball, and a spatial error map is generated and integrated into the digital twin.

During operation, the operator loads the CAD model of the part into the digital twin. The digital twin performs virtual measurements, selecting optimal contact points and probe trajectories that minimize the overall error and measurement time. The generated program is transmitted via the control and measurement system to the physical CMM, which performs the measurements automatically. After the measurements are completed, the twin, using its models, produces not only the point coordinates but also an uncertainty estimates for each measured value, as well as diagnostic information on the current accuracy of the CMM

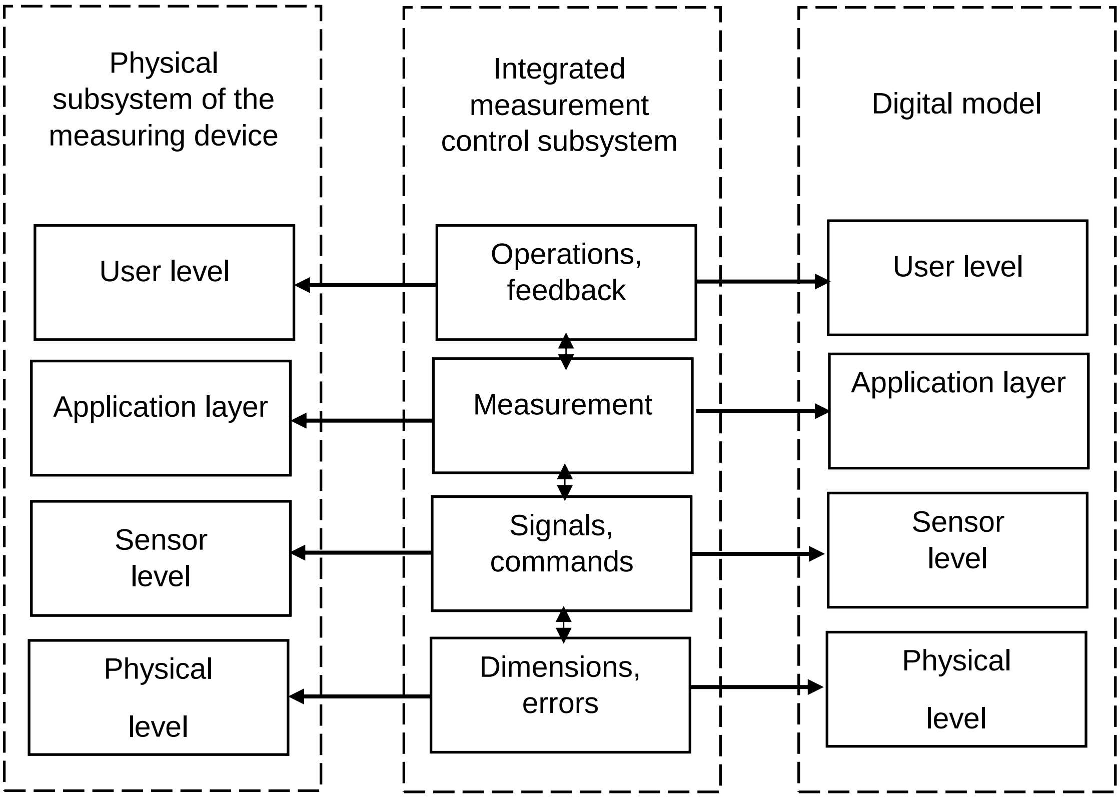

Fig. 3. Physical subsystem of the measuring device.

5. Discussion of Results and Advantages. Implementation of the proposed method and system for constructing a measuring instrument based on a digital twin lead to a qualitative change in the entire lifecycle of high-precision metrology equipment. Table 1. Analysis of the results demonstrates a range of significant advantages over traditional approaches to design, production, and operation.

Table 1. Comparative Analysis with the Traditional Approach:

Criteria	Traditional approach	Digital twin approach
Error Accounting	Disjointed, stage-by-stage; the system model is built post factum.	Holistic, end-to-end; the model is formed iteratively from the very beginning.
Measurement Process	Operator dependent; trajectory planning is empirical.	Automated; the trajectory is optimized virtually based on models.
Result Information	Coordinates of points.	Point coordinates + uncertainty assessment + device condition diagnostics.
Maintenance	Regulatory, according to schedule.	Predictive, based on the actual state.
Traceability	Fragmentary, on paper media.	Complete, in the form of a single digital history.

Digital twin technology creates a virtual replica of a physical measuring instrument, mirroring its behavior and characteristics in real time. This complex system consists of four key components: the physical object itself (e.g., a sensor or pressure gauge), a virtual model, a continuous data stream via IoT devices, and an analytics engine that uses AI algorithms to generate predictions. Using a three-layer knowledge graph architecture, including a conceptual layer for knowledge standardization, a model layer for the digital embodiment of the instrument, and a decision-making layer for operator support, enables the management of measurement systems to be taken to a whole new level.

One of the key achievements is increased accuracy and optimization of calibration, as the digital twin continuously compares current readings with reference standards, enabling automatic recalibration at the slightest deviation. Practical validation of this technology in the production of aircraft engine blades yielded impressive results: the maximum contour error decreased from 0.073 mm to 0.062 mm, and the product availability rate increased from 81.3% to 85.2%. Furthermore, digital twins enable predictive maintenance by predicting potential failures before they occur, which, for example, has reduced torque sensor downtime by 30% in the automotive industry.

The technology also contributes to increased operational efficiency and environmental friendliness by optimizing instrument interactions with other systems and reducing energy consumption. An iterative process of continuous self-updating the model based on feedback ensures that the system flexibly adapts to equipment wear and changing market demands.

Despite challenges such as the complexity of integrating heterogeneous data and the high computing power required to process millisecond-scale data, digital twins remain a key tool for Industry 4.0. In the future, integration with blockchain technologies and the development of autonomous systems could lead to the creation of fully self-repairing and self-optimizing measuring instruments.

Conclusion.

The developed method and system for constructing a measuring instrument based on digital twin technology represent a complete methodology for end-to-end lifecycle support of high-precision metrology equipment. The integration of real-world error data at all stages—from component to operating system—into a dynamic virtual model not only significantly improves measurement accuracy and reliability but also enables a fundamentally new level of intelligent control over the measurement process and the technical condition of the instrument. This approach is a promising direction for the development of Industry 4.0 in precision metrology and mechanical engineering.

References.

1. Hocken, R. J., & Pereira, P. H. (2016). *Coordinate Measuring Machines and Systems*. CRC Press.
2. Schwenke, H., Knapp, W., Haijtema, H., Weckenmann, A., Schmitt, R., & Delbressine, F. (2008). Geometric error measurement and compensation of machines—An update. *CIRP Annals*, 57(2), 660-675.
3. Glaessgen, E., & Stargel, D. (2012). The digital twin paradigm for future NASA and US Air Force vehicles. In *53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference* (p. 1818).
4. ISO 10360-2:2009. Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 2: CMMs used for measuring linear dimensions.
5. Sartori, S., & Zhang, G. X. (1995). Geometric error measurement and compensation of machines. *CIRP Annals*, 44(2), 599-609.
6. Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital twin in industry: State-of-the-art. *IEEE Transactions on Industrial Informatics*, 15(4), 2405-2415.