euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025
www.euspen.eu

Some advances in metrological digital twins for 3D robotic scanning system

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Abstract

This research shows advances in the development of Digital Twins (DTs) by integrating metrological elements to improve precision and reliability in virtual measurements within robotic 3D scanning systems. By focusing on uncertainty estimation as outlined in the Guide to the Expression of Uncertainty in Measurement (GUM), the study applies advanced metrological principles to DTs. As robotics continue to transform sectors under the Industry 4.0 framework, this work presents an advanced DT model for a 3D robotic measurement system, accurately reflecting the physical system's behavior through detailed modeling of both the robot and sensor. Improvements were identified through methods like sensor characterization, robot self-calibration, and sensor self-referencing.

The study enhances current practices by embedding uncertainty estimation directly within the DT, guided by GUM protocols, to ensure measurements meet manufacturing tolerances even before physical testing. Through various sensor tests, both systematic and random uncertainties were determined, allowing the model to simulate demanding operational conditions accurately. Beyond uncertainty estimation, the model incorporates virtual optimization to refine scanning strategies for maximum accuracy while balancing measurement times.

The outcome is a metrologically traceable DT that significantly enhances the accuracy and reliability of robotic scanning systems in manufacturing. Although initially focused on additive manufacturing, this DT holds strong potential for application across diverse industrial fields. As a forward-looking element, the DT also supports estimating real process uncertainty based on experimental data, making it a robust tool for future technological advancements.

Metrology, digital twin, robotics, laser scanning

1. Framework of the work

The importance of modeling and simulating real-world processes is growing, leading to the rise of **Digital Twins (DTs)**—virtual replicas of physical systems that dynamically exchange data with their real counterparts. To ensure confidence in simulations, metrology establishes rules for validating results, similar to real-world measurements, while also accounting for measurement uncertainty [1].

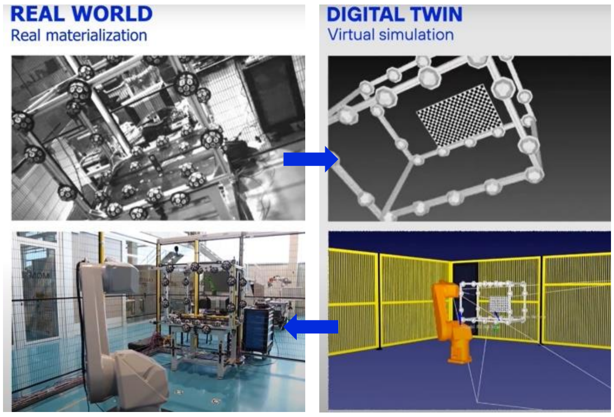

Figure 1. Case study of the project, robotic arm and photogrammetry artefact for scenario calibration

However, traceability and uncertainty quantification in DTs remain challenges. The ISO 23247:2021 standard addresses DT implementation in manufacturing but does not cover uncertainty quantification. To advance research, the EU-funded ViDiT project is working on trustworthy virtual experiments.

2. Development of a traceable DT

The development of traceable Digital Twins (DTs) requires a structured approach to ensure accuracy and reliability in virtual simulations. One critical aspect is establishing a well-defined measurement chain that accounts for key elements contributing to uncertainty.

Elements of the Measurement Chain:

1. Robot Position – The precise position of the robot is crucial for reconstructing the measurements.
2. Referencing of Sensor to Robot – The relative transformation between the robot's flange and the sensor's coordinate system must be accurately determined.
3. Sensor Acquisition – The sensor captures a 2D projection line within its coordinate system, influencing the measurement outcome.

These three factors represent the primary sources of uncertainty in the measurement process. Considering the traceability of the system, it is considered a Digital Twin relies on continuous communication and optimization between the virtual and real worlds through next key steps:

- Real-time data exchange to synchronize DT parameters with actual conditions.
- Regular calibrations to update and refine the DT model.
- Uncertainty estimation using calibrated parameters for more reliable measurements.
- Implementation of optimized strategies to improve measurement accuracy.
- Data-driven decision-making based on refined DT models.

By integrating these principles, Digital Twins can achieve traceability and provide trustworthy simulations for advanced applications.

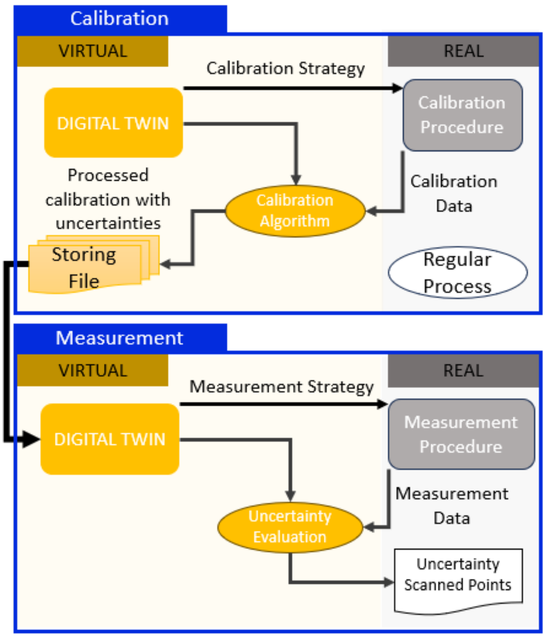

Figure 2. Scheme of proposed workflow for traceable digital twins in measuring systems

3. Traceablility of the DT sensor: Uncertainty and accuracy

Ensuring the traceability of a Digital Twin (DT) sensor requires a structured approach to calibrating and characterizing its performance. Key aspects include self-calibration, process calibration, and advanced modeling techniques to integrate physical measurements into the virtual environment.

Calibration methods to minimize uncertainty and improve accuracy, several calibration strategies are employed. Those methods are enumerated below:

- Robot and referencing parameters through self-calibration.
- In-process calibration for real-time adjustments.
- Using a calibrated artifact to ensure measurement consistency.
- Scanning from different positions to capture diverse data points.
- An automatic and integrated process for efficiency.
- Optimized algorithms based on sensitivity and correlation analysis.

Sensor parameters and periodic updates are studied to ensure the reliability of DT simulations. Key aspects include offline calibration for baseline accuracy, the use of special artifacts for vision system calibration, and regular updates of calibrated parameters to maintain precision.

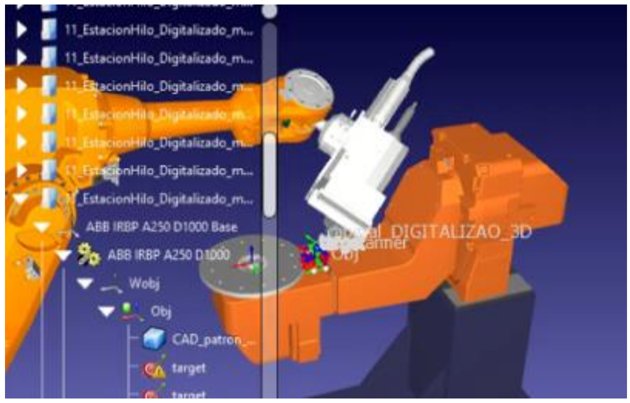

Figure 3. Simulation of robotic arm and the calibration procedure

4. From Physical to Virtual: Data Transfer Process

To feed the Digital Twin with real-world data, the following steps are required. First step is the comparison with nominal values to assess deviations, and filter the signal to remove noise and inconsistencies extrapolating values across the full sensor range. After that, two output maps are generated:

- Uncertainty Map – Represents measurement variations.
- Systematic Error Map – Identifies consistent deviations.

The measurement process is simulated for full DT integration, including CAD file loading to virtually recreate the physical environment, occlusion modeling to account for real-world visibility limitations, and sensor accuracy and uncertainty projections onto the part surface. In the next figure is presented the first results of the research that is on going:

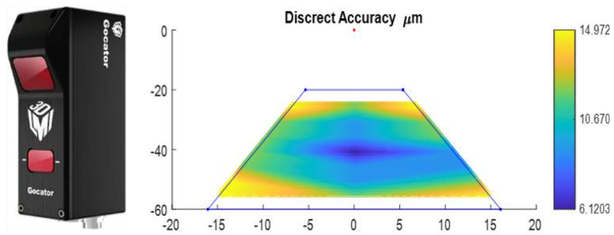

Figure 4. Preliminary results of predicted accuracy for the sensor used in the project

Acknowledgements

This project is developed within the VIDIT project (Trustworthy virtual experiments and digital twins): “The project (22DIT01 ViDiT) has received funding from the European Partnership on Metrology, co-financed from the European Union’s Horizon Europe Research and Innovation”

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