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Digital Twin concept of a force measuring device based on the finite element method

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ABSTRACT
In the framework of EMPIR project ComTraForce, the Digital Twin (DT) concept of force measurement device is developed. DT aims to shade static, continuous as well as dynamic calibration processes, preserving data quality and collecting calibration data for improved Decision-making. To illustrate the developed DT concept, a prototype realisation for static and continuous force calibration processes is developed, involving simulation with ANSYS engineering software. The focus of the current work is placed on the data connection between the physical device and the DT. The DT model is validated using traceable measurements.

Section: RESEARCH PAPER

Keywords: digital twin, force measurement, finite-element-method, measurement uncertainty, traceability, data transfer

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1. INTRODUCTION

In accordance with Industry 4.0 requirements for automation and data exchange, EMPIR project ComTraForce 18SIB08 [1] was taken to develop the prototype of DT of a traceable force transfer standard. The DT is built on the basis of models for static and continuous force transfer standards including measurement uncertainty determination. DT is a management and certification paradigm [2] which allows in real time to predict, optimise and maintain desired functionality of complex systems. Whilst the DT literature has immensely proliferated in recent years, covering various topics such as through-life monitoring and manufacturing, the widely accepted concept of DT was proposed by Grieves [3] and Vickers [4], which identified the following main components: the physical object in real space, the virtual object/model in virtual space and the connections of data and information that ties the virtual and real products together, as shown in Figure 1.

Other authors have reviewed and refined the DT definition [5] establishing a stronger link to Industry 4.0 and its enabling technologies: “DT is the virtual and computerised counterpart of a physical system that can be used to simulate it for various purposes, exploiting a real-time synchronization of the sensed data coming from the field”.

From a standardization work perspective, ISO 23247-1 defines DT as a manufacturing fit-for-purpose digital representation of an observable manufacturing element with synchronization between the element and its digital

Figure 1. Digital Twin concept of Grieves [3] and Vickers [4].

representation [6]. A digital format for the secure transmission and unambiguous interpretation of measurement data is defined in [7].

All DT definitions lead towards a digital representation, or models, of the physical object, process or service, also called Virtual Twins. The Virtual Twin is able to predict the characteristics of the Real Twin with specified precision in real time, which is established by the needs of each specific application for accuracy and decision speed [8]. The DT models are divided into three main categories:

- Physics-based models (Finite Element Method - FEM, structural health monitoring, computational inverse methods);
- Data driven model (Machine Learning, digital signal processing, statistical inverse methods);
- Surrogate model as a combination of both.

A comprehensive overview of the DT model requirements is given, among others, in [8]. The DT model must be able to reflect the physical processes, influencing the output parameters. The accuracy of the predicted values should be high enough to be beneficial for the desired application. Furthermore, the speed of computation must be high enough for real time execution of the DT. Whilst FEM is using current knowledge and off-line measurement results to predict the output of the Real Twin, in DT context, the Virtual Twin requires real time sensors information gathered over the entire operational lifetime [8].

The aim of the current work is to develop the prototype of the DT for static and continuous force calibration processes. To achieve this aim, the Finite Element Analysis (FEA) is chosen for the force measurement device output prediction. However, in order to achieve the required speed of DT execution, several simplifications on the geometry, material behaviour, etc., are made. The Details on the development of the Finite Element model (FE-model) for static and continuous calibration tests with the focus on applicability for DT are provided. A way to connect the force measurement device information with the developed FE-model in an automatised way is presented. At the end, the approach for the physical-to-virtual and virtual-to-physical data communication is also discussed.

The current paper is structured as follows. In section 2 an overview over related literature is given; section 3 presents a concept of DT of force measurement device, addresses the DT definition as well as lists the Digital Metrological Twin requirements. The creation of FE-model of the force measurement device is presented in section 4. The data communication approach between the FE-model and the real device is discussed in section 5. In section 6 the main conclusions of the work are summarised, providing the outlook on the planed DT developments.

2. RELATED WORK

The DT developed in [9] leverages FEM to predict the complex micro-mechanical evolutions of materials during multistage processes on the example of sintering. The focus is placed of the interoperability and robustness of the material data between various FE-steps. A tensile test system, equipped with the optical system to capture full-field geometric images, was investigated in [10]. The DT based on FE modelling is used to ensure that the data, collected by the experimental system, can be used quickly and efficiently to prove theoretical models and to determine required material properties. In [11] the FEM is used for the characterisation of a 5 MN·m torque transducer. The FEM is implied to extend the calibration range up to 5 MN·m level. The method for determination of the Young’s modulus is presented, and the defined value is used in FE-model. The simulated output signal deviates from the measured one by 17.5 %. Another simulation of a 4 kN·m self-built torque transducer in MATLAB Simulink is reported in [12]. The simulation method was developed with a focus on giving recommendations regarding the element type and size. Also, different modelling strategies for the strain gauges are proposed. A deviation between the simulated and measured results down to 1.3 % was achieved. As the most suitable FE element type for the modelling the fully-integrated hexahedral element with quadratic formulation was chosen.

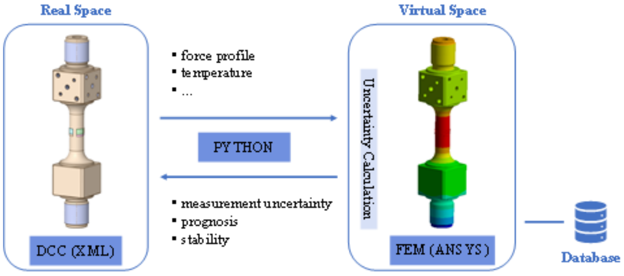


Figure 2. Developed concept of Digital Metrological Twin.

3. DIGITAL TWIN OF FORCE MEASUREMENT DEVICE

DT in metrology requires specific definitions, clearly stated obligatory requirements for measurement traceability. German National Metrology Institute PTB developed the following definition of the Digital Metrological Twin (DMT) [13]: a Digital Metrological Twin is a numerical (prediction) model that depicts a specific measurement process and indicates an associated measurement uncertainty for a specific measurement value, which is traceable to the units of the international system of units. Moreover, it complies with the requirements that:

- the measurement uncertainty is calculated according to recognised standards [14];
- all input parameters are traceably determined and stated with the corresponding measurement uncertainty [14];
- and it is validated by traceable measurements.

Previous definition provides the requirements by fulfilment of which the generated DT output can be utilised for metrological services.

DMT is the enhanced way to generate, process, and store data on a calibration device with the time stamp. Beyond the concept of a digital calibration certificate (DCC) [15], where calibration data is collected, DMT will allow to correlate the force transducer output with the physical processes occurring in the transducer and allows its seamless connection with the Factory of the Future. All relevant data in such database is traceable and represented with SI units, if applicable. This data can be used by the end user in the further life-cycle of the calibrated device. Furthermore, the use of DMT will allow calibration system to learn from itself and reduce the measurements uncertainty for future calibration processes with the same device as well as deliver data to derive correlations between calibration conditions, mounting, etc. as well as output values for devices of the similar class.

The concept of force measurement device DMT covers three main functions, Figure 2. The first function allows for a prompt reading of selected device information, e. g. sensors reading

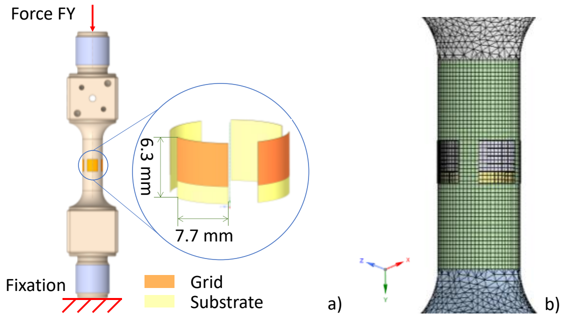


Figure 3. Simulation model of force transducer and strain gauges: a) geometrical model; b) finite element mesh of measurement region.

(temperature and strain). Here the speed of communication as well as preservation of data quality play the key role. The physical-to-virtual communication is realised by reading the relevant device information from a DCC for force measurement. The second function of a DT is the data processing by means of one of three models mentioned above [16]. The main outcome of data processing is the prediction of force measurements device output as well as measurement uncertainty.

For the DMT it is crucial that the input/output parameters are traceable and are stated with the corresponding measurement uncertainty. Additionally, the validation of the static, continuous and dynamic models within DT must be performed using traceable measurements. The third function enables saving of the modelled output which can be used to recalculate uncertainty in future calibration procedures.

As first prototype of DMT of a force measurement device, the FE-model of the transducer is developed. As first attempt, the models of static and continuous calibration processes are developed in FE simulation software ANSYS, see section 3. The synchronization between the force measurement device and its DT is performed after each calibration process in form of reading and subsequent update of the DCC by means of Python v3.9. The calculated DT device output as well as measurement uncertainty are saved after each calibration in a database. The corresponding database of DT represents the device history, allowing the DT to recall any state of the device history. Visualisation of data is realised with matplotlib library v1.3.0.

4. FINITE ELEMENT ANALYSIS

4.1. Numerical model set up

The development of the transducer design is discussed in details in [17]. More details on the creation of digital construction of the transducer are provided in [18]. The transducer is mounted on the 20 kN calibration machine available at PTB. The machine works according to the principle of the direct loading. The weight forces generated by the mass bodies are introduced to the transducer via a load hanger. The load bodies are arranged in such a way that transducers with nominal forces of 2 kN can be calibrated in 12.5 % steps and with nominal forces of 5 kN, 10 kN and 20 kN in 10 % steps according to DIN EN ISO 376

The geometrical model was simplified to the transducer itself and strain gauges in order to enable fast run of the simulation, see Figure 3a). The material of the transducer is quenched alloyed steel 1.6580 QT. The strain gauge is simulated as a polyimide substrate and a grid made of constantan. The contribution of the glue layer is neglected. The transducer is partially meshed with the tetragonal TET10 elements with the size of 2 mm size. The strain gauges as well as the transducer region, close to strain gauges placement, are meshed with hexagonal HEX20 elements to ensure better mesh consistency, see Figure 3b. The element size of 0.6 mm was set for HEX20 elements. Further element size refinement below 0.6 mm led to no significant improvement of the simulated output signal.

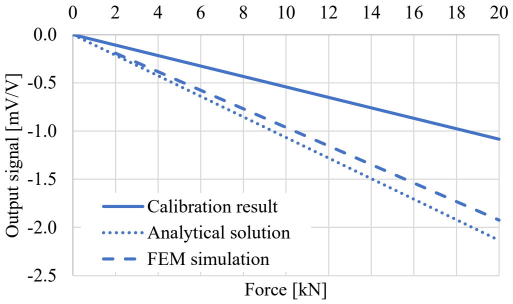


Figure 4. Simulated and experimentally measured output signal.

4.2. Static force model

To investigate the influence of static forces on the measured signal of transducer, the static mechanical analysis with ANSYS was set. The concentrated force F_Y was applied stepwise in axial direction to reproduce the loading during calibration experiments, until the nominal value of 20 kN was achieved. Boundary conditions $U_X = U_Y = U_Z = UR_X = UR_Y = UR_Z = 0$ were applied on the opposite side of the transducer, simulating transducer mounting in the loading train. Elastic material properties of 1.6580 steel [19], polyimide [20] and constantan [21] were defined, see Table 1.

4.3. Continuous force model

During continuous calibration tests, output signal variation with time under the application of a constant load is observed. In force measurement industry this phenomenon is defined as creep [22]. One of the physical mechanisms, leading to the output signal variation, is the superposition of the thermoelastic strains in the load cell itself as well as the strain of the strain gauge materials. To simulate this effect the transient coupled field analysis in ANSYS was performed. A key role in the model is played by the definition of the thermal material properties, such as heat expansion coefficient, specific heat and thermal conductivity, [19], [20] and [21], see Table 1. Simulated compression load was applied in axial direction for 20 s up to maximal nominal value of 20 kN and subsequently held for 600 s. The full unloading was simulated for 20 s as well and the final strain was measured after 600 s, capturing unloading creep.

4.4. Simulation results

To validate the developed FE-model, the static as well as creep calibration experiments according to ISO 376:2011-09 with the nominal force of 20 kN were performed. A comparison of the simulated output of the strain gauge bridge after static loading profile with the experimental measurements and analytical solution [18] is presented in Figure 4.

Table 1. Material properties of the transducer materials used in ANSYS

Material property	1.6580 QT	Constantan	Polyimide
Young's modulus in GPa	210	162	2.65
Poisson's ration	0.33	0.31	0.37
Thermal expansion in 1/K	$1.11 \cdot 10^{-5}$	$8.3 \cdot 10^{-6}$	$5.5 \cdot 10^{-5}$
Specific heat in J/(kg K)	460	390	1090
Thermal conductivity in W/(m K)	42	21.8	0.33

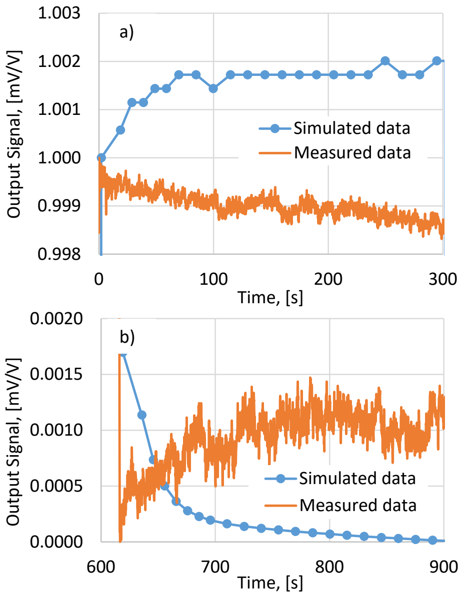


Figure 5. Simulation model of force transducer and strain gauges during a) loading and b) unloading.

The discrepancy between the simulated result and the analytical solution lies around 9.8 %. For the reliable DT functionality, the precision must be improved, for example through the consideration of the glue layer contribution.

Similar to the static calibration test model, the FEA output signal lies close to the analytical value, which is twice higher than the experimental one. To enable better data comparison, the measured as well simulated output signals were normalised using the formula (1):

$$X' = \frac{X - X_{\min}}{X_{\max} - X_{\min}}, \tag{1}$$

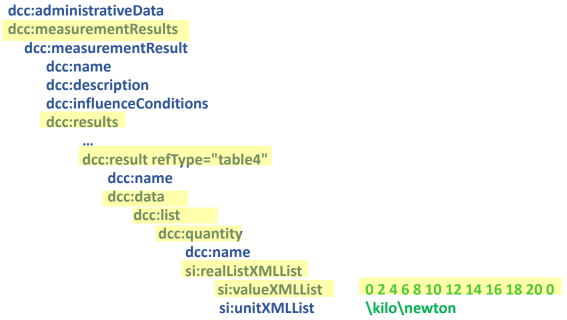
where X' is the normalised value, X is the measured value to be normalised, $X_{\min}$ and $X_{\max}$ minimum and maximum values of the dataset respectively. The simulated output signal of the load cell is presented in Figure 5a during loading and in Figure 5b during unloading. The output signal was calculated using simulated total strain values, which were derived as the sum of elastic and thermal strains. The simulated and measured data show opposite trends. The measured data represents the strain gauge output signal and the simulated one of the load cell output. This is in accordance with findings of Kühne, who stated that creep recovery of the load cell acts in opposite direction to the creep of the strain gauge and the corresponding glue layer [22].

Measured creep results showed output signal deviations due to creep of 0.214 % and 0.211 % after loading and unloading correspondingly. The simulated results reported 0.45 % and 0.47 % output signal deviations for loading and unloading. Thus, both static as well as continuous simulations show almost double signal value in comparison to the measured values.

5. DATA COMMUNICATION

5.1. Data input

The physical-to-virtual communication is realised by reading the relevant device information from a DCC in XML format. The benefit of direct use of data from DCC is that the resulting data is provided in SI format. The data transfer from DCC ensures that the input parameters of DT are traceable and stated with the given measurement uncertainty, as required by the definition of DMT.



```
dcc:administrativeData
dcc:measurementResults
  dcc:measurementResult
     dcc:name
     dcc:description
     dcc:influenceConditions
     dcc:results
        ...
          dcc:result refType="table4"
             dcc:name
             dcc:data
                dcc:list
                   dcc:quantity
                      dcc:name
                      si:realListXMLList
                          si:valueXMLList     0 2 4 6 8 10 12 14 16 18 20 0
                          si:unitXMLList      \kilo\newton
```

Figure 6. XML Tree structure of force DCC and highlighted list element containing values of applied force magnitude in kN.

```
# Importing element tree under the alias of ET
import xml.etree.ElementTree as ET

# Passing the path of the xml document to enable the parsing process
tree = ET.parse(DT_directory/’Example_DCC_ISO 376_22999.xml’)

# Getting the parent tag of the xml document
root = tree.getroot()

# Print force magnitude values in kN from DCC
print(root[1][0][3][3][1][0][0][1][0].text)
```

Figure 7. Code example demonstrating navigation to specific DCC element.

The DCC for static force calibration process was developed at PTB in accordance with the XML scheme (XSD) 3.1.2 [23]. To read input parameters from DCC, the ElementTree XML API v1.3.0 was used [24]. It allows to read the specified elements of DCC XML tree, see Figure 6.

An example of code allowing to navigate in the required DCC element is presented in Figure 7. The code is strongly related to a specific DCC structure and must be adjusted in case of any modifications of DCC XML Tree.

The collected data are transferred as loading and boundary conditions of FE-simulation in form of Python command. The entire FE-model was built in ANSYS Mechanical 2021 R1 using Mechanical Python APIs to automate the process [25]. The application diagram, showing input output data flow of the developed DMT software is presented in Figure 8.

5.2. Data output and storage

The calculated DT force transducer data are used to calculate measurement uncertainty considering effects from the mechanical system and surrounding the force measurement device. In future developments, the collection of the selected information in a database will be realised. Each dataset will be

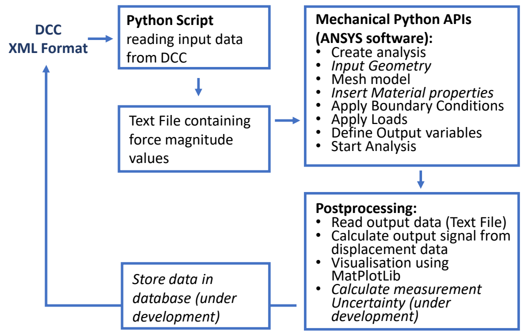


Figure 8. Application diagram illustrating developed DMT software.

completed with the metadata stating the calibration time. In this way the continuous calibration history of the force measurement device will be created.

6. CONCLUSIONS AND OUTLOOK

A digital replica of the force measurement device based on FE-model is created in this work. The first results of force transducer output for static and continuous calibration processes are obtained. The static results are in good agreement with the analytical solution. The simulated output signal values were on average twice large as measured values, which points out on the necessity of checking the bridge wiring potentially affecting results interpretation. In future works it is planned to extend DT model with the dynamic calibration process models. The developed concept of the DT will be applied to estimate the effect of not proper mounting, material properties as well as parasitic force components on the measurement uncertainty. By combining the obtained simulation data with the experimental one and analysing both with the Machine Learning algorithm, the surrogate model will be created.

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