

# Research on Digital Methods for Testing and Calibration Schemes

QI Yulin, CUI Weiqun, LIU Xinmeng\*

*National Institute of Metrology, Beijing, China, liuxm@nim.ac.cn*

**Abstract** – To adapt to the digitalization of product design, a digital model and establishment method for testing and calibration schemes are proposed, which are used for the digital modeling and simulation verification of testing and calibration schemes. This method uses the System Modeling Language (SysML) to construct a digital model of the testing and calibration scheme. Taking the calibration scheme of a typical optical measuring instrument as an example, a digital model is built based on MBSE software, and simulation verification and processing analysis are carried out in combination with measured data. The empirical results show that the proposed digital method provides a unified model architecture for the testing and calibration schemes in metrological design, which can facilitate the rapid establishment of digital models and virtual simulation verification. The proposed method is adapted to the digitalization of product design based on MBSE, filling the gap in the digital method for testing and calibration schemes in metrological digitalization.

**Keywords:** *Metrology, Product design, Digital model, MBSE, Virtual simulation, SysML*

## I. INTRODUCTION

Metrology digitization represents the global development trend in metrology. Driven by research institutes such as the International Bureau of Weights and Measures (BIPM) and Physikalisch-Technischen Bundesanstalt (PTB), the digitization of metrological results has reached a mature stage, with the establishment of specifications like Digital International System of Units (D-SI) and Digital Calibration Certificates (DCC) [1]. The National Institute of Metrology, China (NIM) has developed formatting protocols and generation algorithms for DCC, which are now under trial in domains such as time-frequency metrology [2]. Notably, the utilization of digital testing and calibration result data hinges on the availability of corresponding digital scheme information. Current frameworks like D-SI exclude calibration scheme descriptions, while DCCs can only document calibration methods in textual form. These limitations render existing metrological digitization tools inadequate for systematic

representation of testing and calibration schemes, and they lack mechanisms for simulative verification.

One of the keys to integrating testing and calibration into product digital design, digital manufacturing, and digital maintenance lies in establishing a scientific and reasonable digital model for testing and calibration schemes. It should involve digitizing static information such as metrological characteristics, calibration conditions, and calibration items, as well as dynamic information including calibration methods, calibration result processing methods, and uncertainty evaluation methods.

Product design paradigm is shifting from traditional Document-Based Systems Engineering (DBSE) to Model-Based Systems Engineering (MBSE), aimed at enabling clear, precise description and management of product architecture, interfaces, and interaction dynamics while meeting demands for information integration and visual analysis [3-6]. In MBSE, digital models serve as irreplaceable cornerstones [7-8]. This integration spans requirements, functional specifications, structural designs, behavioral patterns, and other dimensions.

This paper establishes a digital model for testing and calibration schemes using SysML based on the MBSE design methodology. Through the simulation and analysis functions of the model, designers can verify the schemes via simulation during the design phase, predict potential issues in testing and calibration processes in advance, and optimize measurement methods and workflows.

## II. DIGITAL MODELING METHODS FOR TESTING AND CALIBRATION

### A. Product Testing and Calibration Scheme Design Process

The testing and calibration process of products is an interactive process involving multiple elements such as personnel, metrological equipment, measured objects, metrological methods, metrological environments, and data [9]. The design process of product testing and calibration schemes generally includes two parts: product metrological

requirement analysis and testing & calibration scheme design [10]. Effective metrological requirement analysis is the prerequisite for carrying out testing and calibration scheme design. Aimed at product metrological requirements, the testing and calibration scheme design gradually clarifies key elements such as testing requirements, methods, interfaces, and testing cycles, completes the design of testing schemes for each parameter, then integrates the testing schemes of each parameter to form a product testing scheme and confirm each testing device. For each parameter of the testing device, according to the parameter calibration requirements, the calibration method, traceability chain, calibration interface, and calibration cycle are determined to form the calibration scheme for the corresponding parameter. The design process of product testing and calibration schemes is shown in Fig. 1.

### B. Digital Methods and Models for testing and Calibration Schemes

As shown in Fig. 1, the design processes and elements of testing schemes and calibration schemes are similar. To avoid repetition, this paper only presents the digital method for calibration schemes. For testing equipment, there are generally multiple parameters to be calibrated, and corresponding parameter calibration schemes need to be designed for each parameter, including parameter calibration requirements, parameter calibration methods, parameter traceability chains, parameter calibration interfaces, and parameter calibration cycles. By integrating the calibration schemes for different parameters of the testing equipment, the equipment's calibration scheme is formed, including calibration requirements, calibration methods, traceability chains, calibration equipment, calibration interfaces, and calibration cycles.

During the transformation and development of product design processes toward MBSE, SysML, an extension of the Unified Modeling Language (UML), which has emerged as a pivotal MBSE modeling language, are widely adopted for digital modeling and analysis in systems engineering [11-12]. SysML provides system developers with standardized graphical and textual representation methods to clearly depict a system's key elements, such as structure, behavior, requirements and their interrelationships [13].

Testing and calibration methods are essentially measurement processes, generally comprising four parts: measurement principles, environmental conditions & control measures, out-of-tolerance judgment methods, and data processing &

uncertainty evaluation methods. Thus, the digital model for calibration schemes in this paper mainly includes these four modules. Kinds of modules are modeled using elements and diagrams in SysML to finally form a complete calibration scheme model as follows:

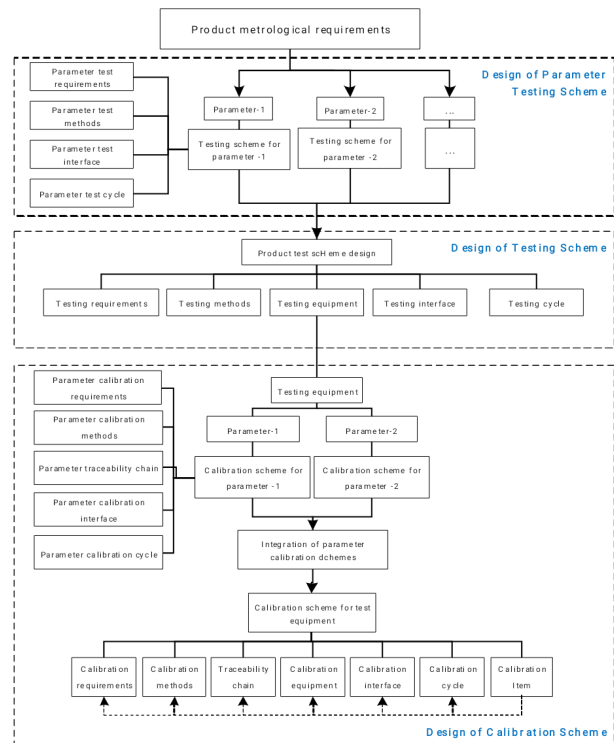


Fig. 1. Testing and Calibration Scheme Design Process.

(1) Calibration Scheme Architecture: Package element is utilized to describe constituent documents and Package Diagram (PKG) is employed to illustrate the scheme's composition, organize and manage model elements. By grouping related elements into distinct packages, the structure of complex system models becomes clearer, more intuitive, and easier to maintain.

(2) Model Composition: Block element is employed to depict model components and Block Definition Diagram (BDD) is used to illustrate model composition, present system modules and their interrelationships in a structured manner.

(3) Internal Structure and Signal Transmission of the Model: Block element is used to describe model components and Port is used to define interfaces, then Block Definition Diagram (BDD) with an Internal Block Diagram (IBD) is utilized to refine the system structure. This diagram primarily illustrates interconnections and interaction relationships

among internal components of a block.

(4) Calibration Activities and Process Description: Activity Diagrams (ACT), State Machine Diagrams (STM), and Sequence Diagrams (SD) are utilized to appropriately model calibration workflows corresponding to calibration methods. Simulation can be employed to verify process correctness.

(5) Calibration Item Simulation and Uncertainty Evaluation: through binding parameter values to calibration method models in a Parametric Diagram (PAR), the correctness and rationality of calibration method models are validated.

### III. CASE STUDY ON THE IMPLEMENTATION OF DIGITALIZATION APPROACHES

#### A. Typical Calibration Scheme for Optical Measuring Instruments

The hemispherical emissometer, which is used to measure the hemispherical emissivity of materials and evaluate their absorption and radiation characteristics, serves as a typical optical measuring instrument. It plays an indispensable role in fields such as material science, aerospace, and building energy conservation [16]. In the product design and manufacturing of related fields, the hemispherical emissometer is an important testing equipment for the thermal physical properties of materials [17]. Taking this as an example, this paper introduces the digital method of the calibration scheme. The MBSE design tool used complies with the SysML specification, and the model-related graphics in the following text are exported from the finally completed digital model of the calibration scheme.

#### B. Digital Model of Calibration Scheme

Overall architecture of the calibration scheme for the hemispherical emissometer is designed using Package elements and a Package Diagram (PKG), as shown in Fig. 2. The overall structure follows the design process illustrated in Fig. 1. First, the calibration object is correctly described as the starting point for designing the calibration scheme. Then, parameter calibration schemes are designed for the main calibration parameters of the hemispherical emissometer. Finally, the calibration schemes for each parameter are summarized, deleted and aggregated to form the equipment calibration scheme, which mainly includes equipment calibration requirements, calibration methods, traceability chains, calibration interfaces, calibration cycles, etc. Meanwhile, calibration items and calibration equipment for the hemispherical emissometer are established.

(1) Digital Model of Hemispherical Emissometer

for Materials

The model of the calibrated object primarily includes the composition of the equipment under calibration, such as internal interfaces and signal transmission, functional descriptions, and usage processes.

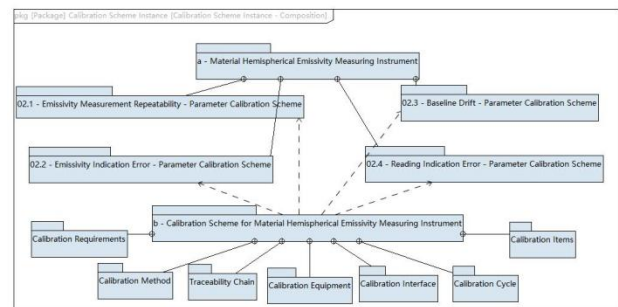


Fig. 2. Composition of Calibration Schema.

As shown in Fig. 3, the Block element is used to establish the model of the calibrated object, i.e., the hemispherical emissometer, and the Block Definition Diagram (BDD) is employed to describe its model composition. To facilitate the subsequent design of the Internal Block Diagram (IBD) and simulation of the calibration process, the model is constructed as a system comprising five components based on the actual functions and composition of the measuring instrument: light source, spectroscopy system, detection system, integrating sphere sample chamber, and control system.

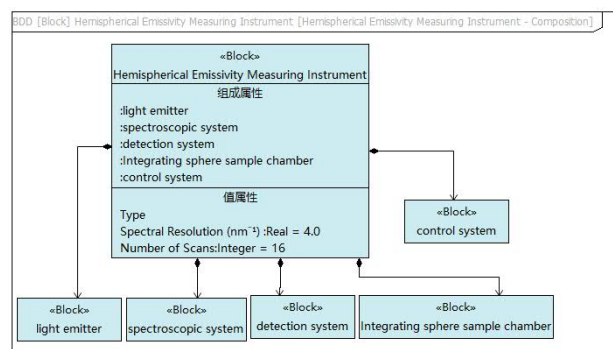


Fig. 3. Composition of Hemispherical Emissometer Model.

Furthermore, the Internal Block Diagram (IBD) is utilized to describe the internal composition of the hemispherical emissometer, including its interfaces and signal transmission, as shown in Fig. 4.

The Activity Diagram (ACT) can be used to depict the relevant measurement process as shown in Fig. 5.

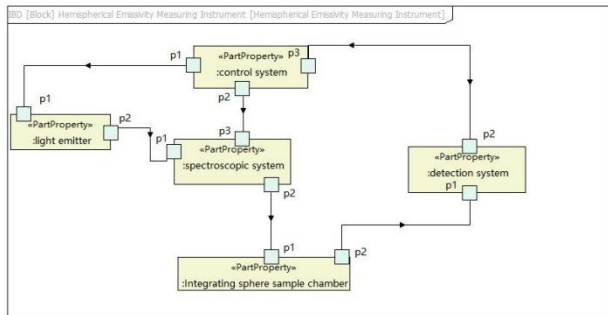


Fig. 4. Internal Signal Flow Diagram of Hemispherical Emissometer.

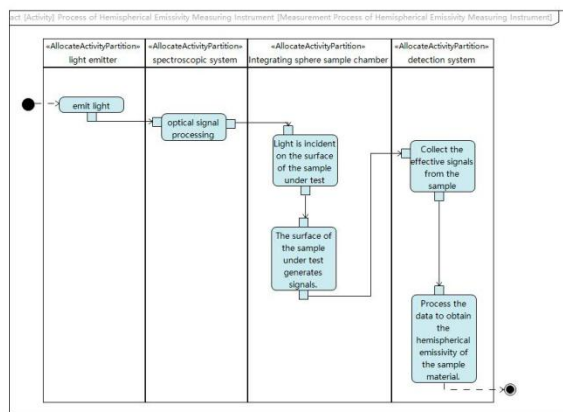


Fig. 5. Measurement Process of Hemispherical Emissometer.

## (2) Digital Model of Baseline Drift Parameter Calibration Scheme

The main calibration parameters of the hemispherical emissometer include baseline drift, emissivity measurement repeatability, wavenumber indication error, and emissivity indication error. The composition of baseline drift parameter calibration scheme can be represented by a Block Definition Diagram (BDD), as shown in Fig. 6.

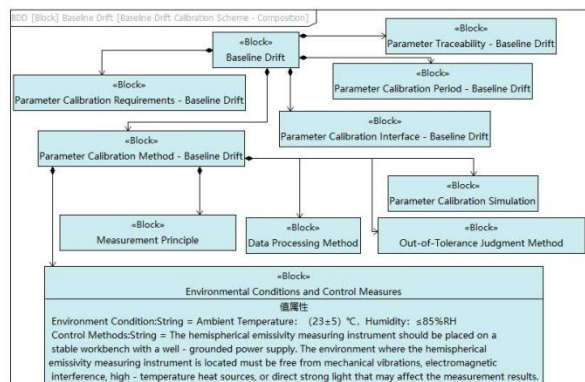


Fig. 6. Baseline Drift Calibration Schema.

The parameter calibration method module further specifies the calibration methods for specific

parameters. For example, the baseline drift calibration method is to select an emissivity standard piece with a nominal value of 0.9 to calibrate the emissivity measurement capability of the hemispherical emissometer, take 1 minute as the measurement time interval, and continuously measure 10 emissivity data. The data processing method is to calculate the relative drift according to Eq. (1).

$$\Delta_{100} = \frac{\varepsilon_{\max} - \varepsilon_{\min}}{\varepsilon_{\max} + \varepsilon_{\min}} \times 100\% \quad (1)$$

Where subscript max is the maximum value among the 10 emissivity data points, and subscript min is the minimum value among the 10 emissivity data points.

The block definition diagram (BDD) is used to establish the baseline drift data processing method model, as shown in Fig. 7.

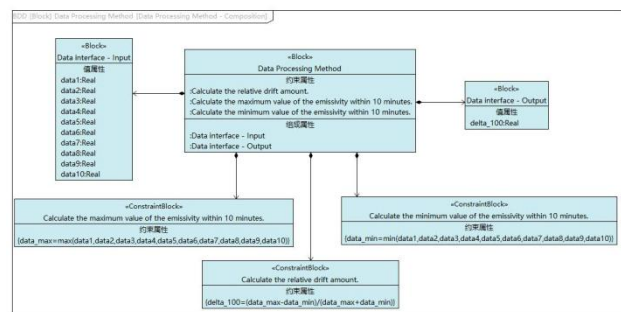


Fig. 7. Composition of Baseline Drift Data Processing Model.

Furthermore, in the Parametric Diagram (PAR), specific parameter values are bound to the data processing model, as shown in Fig. 8, to complete the construction of the baseline drift data processing model calculation simulation program.

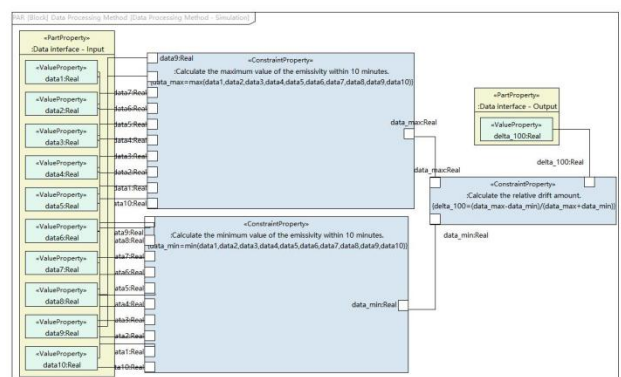
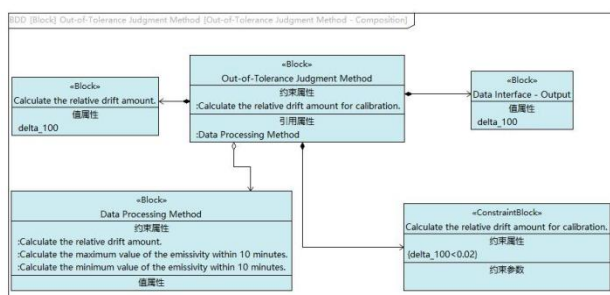


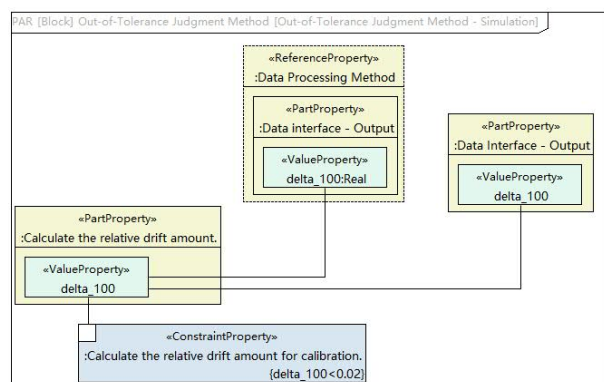
Fig. 8. Baseline Drift Data Processing and Calculation.

For the calculated baseline drift, the out-of-tolerance judgment method in the calibration scheme can set limits for the calibration results. For

example, the baseline (100% point) drift of the hemispherical emissometer is required to not exceed 0.02, based on which out-of-tolerance judgment can be made. Similarly, the Block Definition Diagram (BDD) can be used to establish the baseline drift out-of-tolerance judgment method model, as shown in Fig. 9. In addition to the data input, data output, and out-of-tolerance judgment modules, the data processing module calls the baseline drift data processing module. In the Parametric Diagram (PAR), the parameter values are bound to the out-of-tolerance judgment data processing model, as shown in Fig. 10, to complete the construction of the baseline drift out-of-tolerance judgment model calculation simulation program.



*Fig. 9. Composition of the Baseline Drift Out-of-Tolerance Judgment and Processing Model.*

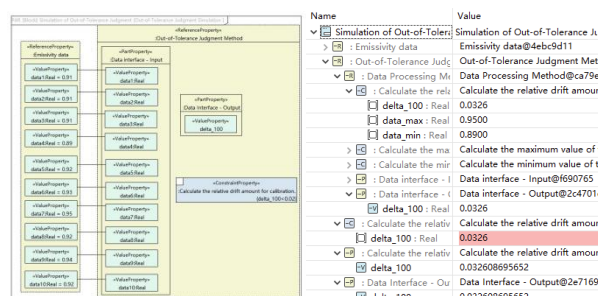


*Fig. 10. Calculation of Baseline Drift Out-of-Tolerance Judgment and Processing.*

After establishing the data processing model, the construction of a specific simulation model can be further completed. Assuming 10 emissivity data points are collected, they are input into the input module of the calibration method simulation model, and the baseline drift out-of-tolerance judgment method is selected as the data processing module to construct a baseline drift out-of-tolerance judgment simulation model.

After establishing the simulation model, Parametric Diagram (PAR) is used to bind the

emissivity data to the input interface of the out-of-tolerance judgment method model. Then, model simulation can be performed. The emissivity data can be processed using the model established earlier. The out-of-tolerance judgment result is shown in Fig. 11. The simulation shows that the baseline drift of this hemispherical emissometer is 0.0326, exceeding the tolerance of 0.02. The judgment result is displayed in red, indicating that it does not meet the drift requirement.



*Fig. 11. Baseline Drift Out-of-Tolerance Judgment Simulation Calculation and Results.*

### (3) Digital Model of Emissivity Indication Error Calibration Scheme

The emissivity indication error also includes the components shown in Fig. 7. The calibration method for the emissivity indication error parameter involves calibrating the hemispherical emissometer using a hemispherical emissivity measurement standard. The measurement model is:

$$\Delta\varepsilon = \varepsilon - \varepsilon_m \quad (2)$$

Where  $\varepsilon_m$  is the calibration value at a specific wavenumber,  $\varepsilon$  is the indication value of the measuring equipment, and  $\Delta\varepsilon$  is the indication error of the measuring equipment. The measurement uncertainty of emissivity mainly originates from measurement repeatability and the emissivity measurement standard.

According to the GUM standard, an uncertainty evaluation model can be established to carry out uncertainty verification. Considering the versatility of the model, Monte Carlo method is used. As an example, it is assumed that the standard uncertainty introduced by measurement repeatability follows a normal distribution with a mean of 0.910 and a standard deviation of 0.007. The standard uncertainty of the emissivity measurement standard follows a uniform distribution with a mean of 0 and a half-width of 0.015. With a confidence probability of 0.95,  $10^6$  Monte Carlo simulations are performed. The

expanded uncertainty of the measurement result for the indication error is:

$$U_{95} = [-0.021, 0.021] \quad (3)$$

#### (4) Digitalization of Calibration Scheme for Hemispherical Emissometer

After designing calibration schemes for each parameter, it is necessary to integrate the calibration requirements, methods, interfaces, traceability chains, and calibration cycles of all parameters to form an equipment calibration scheme. Meanwhile, suitable standards should be selected as the calibration equipment for the testing equipment by synthesizing the calibration schemes of all parameters. For example, in the calibration scheme of the hemispherical emissometer, calibration equipment such as emissivity standards with nominal values of 0.1, 0.3, 0.5, 0.7, and 0.9, as well as polystyrene infrared wavelength standard materials, are selected by integrating calibration requirements such as baseline drift and emissivity indication error.

#### IV. RESULTS

Empirical results in this paper show that the digital method proposed in this paper can provide a unified and effective model architecture for product inspection and calibration schemes. In the follow-up research, the control and data interaction methods with the digital twin models of testing and calibration equipment will be further studied.

#### V. ACKNOWLEDGMENTS

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