ACTA IMEKO
ISSN: 2221-870X
March 2026, Volume 15, Number 1, 1 - 5

Innovative approaches in digital metrology: Advancing calibration and management through Industry 4.0 technologies

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ABSTRACT
To address the new metrological challenges brought about by the digital revolution, a series of projects has recently been developed worldwide with the primary aim of promoting a new infrastructure for digital legal metrology. These projects include the use of cloud technologies to support conformity assessment processes, the development of infrastructure for digital calibration certificates, research on the comparability of real and virtual measurements, and the development of assessment methods for machine learning and artificial intelligence. The objective of the present paper is to present Pandora IRTech, a calibration and management software that utilises concepts and technologies from the Fourth Industrial Revolution. The software was built from a conceptual model based on state-of-the-art studies, process mapping, and risk assessment, identifying optimised structures and functionalities for its development. Finally, the applications created to optimise the calibration process and laboratory management in the current context of the digital revolution in metrology are presented and discussed.

Section: RESEARCH PAPER

Keywords: digital metrology; Industry 4.0; calibration processes; management processes; measurement; software

Citation: I. F. M. Garcia, J. S. Ferreira, M. V. L. Oliveira, E. M. Macedo, M. V. T. Navarro, J. G. P. Peixoto, Innovative approaches in digital metrology: Advancing calibration and management through Industry 4.0 technologies, Acta IMEKO, vol. 15 (2026) no. 1, pp. 1-5. DOI: 10.21014/actaimeko.v15i1.1957

Section Editor: Carlos Hall, PósMQI/PUC-Rio, Rio de Janeiro, Brazil

Received October 25, 2024; **In final form** August 29, 2025; **Published** March 2026

Funding: Financial support provided by the National Nuclear Energy Commission (CNEN), Brazil.

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1. INTRODUCTION

"There is nothing more difficult than to take the lead in introducing a new order of things, for innovation comes with challenges, risk, and uncertainty of success" [1]. Sixteenth-century philosopher Niccolò Machiavelli's observation remains pertinent, particularly when changes set a new course in fields like metrology. This sentiment resonates within the paradigm of the digital revolution, characterized by rapid technological transformation that fundamentally redefines how we live, work, and relate. Today, this revolution actively shapes metrology, offering new benefits and challenges to society.

The Fourth Industrial Revolution, or Industry 4.0, has radically transformed organizational operations and production processes. Defined by the convergence of digital, physical, and biological technologies, this revolution integrates digital advancement as a core driver of transformation. Metrology has become deeply embedded in this paradigm, experiencing its own "digital revolution" [2].

With the rapid progress of digital transformation, technologies aligned with the 4.0 model, such as Artificial Intelligence (AI), are entering the medical domain at an increasing rate, presenting new metrological challenges. AI applications in healthcare are driven by potential cost savings, enhanced patient outcomes, and advancements in measurement technology. AI holds promise, for instance, in addressing the challenge of processing vast data volumes. Imaging procedures generate substantial data every year that is practically impossible for professionals to assimilate and interpret promptly. AI may accelerate the assimilation of knowledge traditionally requiring years of medical expertise, allowing new information to be processed and integrated efficiently. However, despite its potential, there remains no formally established standard of trust for AI metrology within the medical field [3].

In this evolving context, calibrating measurement equipment is essential for ensuring the accuracy and reliability of measurements. Combining calibration with Management 4.0 introduces an innovative approach that leverages advanced technologies and intelligent systems to enhance the efficiency and dependebility of calibration processes. The integration of cloud computing, internet-based applications, virtual technologies, and Artificial Intelligence further streamline processes, fostering higher efficiency.

Within the framework of Metrology 4.0, the significance of mathematical and physical simulations and computer-based experiments is rapidly increasing. Such simulations can replicate both measuring devices and actual measurements, functioning as “virtual measuring instruments.” Here, the task of metrology is to establish trust in simulation-derived results and ensure that calibration conditions align with those in real measurements [3].

Recently, several international projects, including GEMIMeG-II, European Metrology Cloud, Met4FoF, Digital-SI Task Group, and SmartCom, have been launched to build the new infrastructure for digital legal metrology. These initiatives focus on developing digital calibration certificates (DCCs), researching the comparability of real and virtual measurements, and advancing evaluation methods for machine learning and Artificial Intelligence [4]. Within this digital transformation, Pandora IRTech was created, harnessing advanced Industry 4.0 technology to optimise laboratory management and calibration processes. This paper aims to present the development and application of Pandora IRTech in calibration laboratories.

2. METHODOLOGY

The application software (Pandora IRTech) was developed from a conceptual model that was conceived from a state-of-the-art study [5] and a process mapping and risk identification study [6] in the metrology technique. The software was developed to meet the operational requirements described in Table 1.

The applications were created in the Power Apps software (Microsoft) to integrate the functionalities developed in Excel (for AI applications, calculations, and automation of the tasks); PowerBI (in the use of data science tools); Foxit Reader (in the encryption of the data), gov.br (advanced electronic signature), and the Notepad++ (32 bit) for adapting the data to the XML Scheme standard, standard for issuing digital calibration certificates (DCCs).

The programming language used to write the codes for automation tasks was Visual Basic for Applications (Microsoft), and the user interface language was Portuguese.

The software validation process verified its ability to meet the requirements and expectations defined for its operation. For this, the following approach was used: 1) operational requirements verification, 2) unit tests, 3) acceptance tests, and 4) security tests.

Table 1. Software operational requirements

Technologies	Management Applications	Calibration Applications
Artificial Intelligence	Order and job management	Integration of technical and administrative records, Automation of tasks, Calculation of errors and uncertainties, Traceability management
Data Science Analytics	Compliance, Risk and opportunity, Finances, Production, Client satisfaction management	Quality controls
Cryptography & Digital Signature	Records control, Issuance of digital calibration certificates	Raw data protection, Conformance of the data to the XML Scheme standard

3. RESULTS AND DISCUSSIONS

To be practical, accessible, universal, and compatible with other programs, the base chosen for the program was the spreadsheet, which can be run by Excel. In fact, this is one of the most used commercial software, and it provides affinity to the users with a familiar interface. Through the Excel format, the users can incorporate spreadsheets with uncertainty calculations already existing in their organization, without the need to host their data in third-party databases or have advanced knowledge in a programming language to manage them.

The software's primary structure is that of rule-based systems, one of the simplest methods for Artificial Narrow Intelligence (ANI) applications. The program works by reading and interpreting data entered into cells, which have been prepared to receive numeric or text data. In this system, a rule is always composed of a premise and a conclusion. The interpretation of these rules is made according to the logical value of the premises. If the value of the premises is actual, it follows that the conclusions are also valid.

Integrating a database system associated with cloud computing enables efficient storage of administrative and calibration data that can be used for descriptive, diagnostic, predictive, and prescriptive analyses of the processes related to the quality system.

The original calibration certificate data (.xlsm) is saved in PDF (human-readable) and XML (machine-readable) format. Then, when the XML Scheme standard is defined and operational in the country, it will enable the issuance of a DCC that will consequently allow users (service providers, industries, regulatory bodies) to automate the critical analysis of the certificates.

3.1. Management applications

The Business Intelligence (BI) approach analyzes the data stored in the database. This technology allows the user to identify trends, patterns, and anomalies in data that might otherwise be difficult to identify. In addition, this application ultimately enables the identification of growth opportunities, improved process efficiency, and cost reduction. In this sense, a series of applications with easily integrated interfaces were created, which help to manage orders and jobs (proposal, calibration report generation, and document and record control), risks and opportunities, compliance (regulatory and normative), production control, financial analysis, suppliers and training, and customer satisfaction evaluation. Figure 1 illustrates some examples.

Figure 1. Illustration of the application models for management (software language: Portuguese).

3.2. Calibration applications

3.2.1. Integration of technical and administrative records

Based on data from the service proposal approved by the client, the software is designed to integrate all administrative records related to each calibration, automatically identifying all instruments, quantities, and calibration ranges, and parameterizing them according to the type of calibration certificate (accredited or non-accredited).

3.2.2. Generation of calibration certificates and spreadsheets

Following the parameterization of quantities, the software generates customized spreadsheet templates for calibrating each specific quantity of equipment. Each template includes the associated calibration certificates and a dedicated calculation sheet tailored for each calibration.

3.2.1. Calculation of errors, uncertainties, coefficients, and statistical inferences in calibrations

A dedicated spreadsheet is generated for each calibration, structured into tables that organize calibration data systematically. When populated with readings from both the standard equipment and the device under calibration, these tables automatically compute errors, uncertainties, calibration coefficients, unit conversions, and statistical inferences to validate the calibration results. Additionally, a graphical output is generated to assist the technician in analyzing the calibration results.

3.3.4. Traceability management

Every standard used in the calibration process must be traceable, with its data updated on the calibration certificate. Although this may seem straightforward, traceability is essential to calibration quality and can be challenging to manage across numerous standards. To address this aspect, a dedicated code was developed to manage the traceability of all calibration certificates. This application automates the verification and updating of traceability information for each standard by querying the laboratory's current calibration plan.

3.3.5. Quality control

Statistical techniques, including control charts and variance analysis, are employed to monitor the stability of calibration processes and to detect any undesirable deviations or trends, ensuring ongoing process quality. Figure 2 shows a control chart screen for illustration.

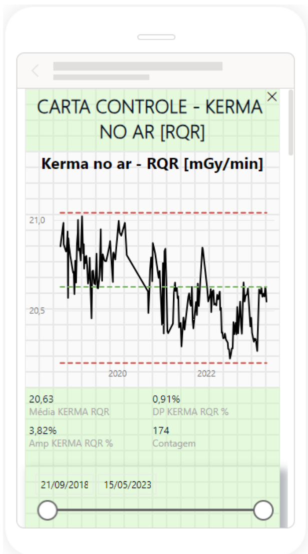

Figure 2. Illustration of the application models of quality control (software language: Portuguese).

3.2.2. Protection of raw data

According to ISO 17025:2017, all technical records must be guaranteed protection against alterations. Therefore, for the protection of raw calibration data, a code was written that allows the user to protect all relevant data and formulas from all calibration spreadsheets with a standard password in a single click. This function is handy for speeding up the process of protecting the calibration data of equipment with many quantities to calibrate, which generate large volumes of data.

3.2.3. Protection of the calibration certificates.

Calibration certificates (in PDF and XML format) are protected using the 128-bit AES algorithm, an advanced encryption standard for preventing document changes. The last layer of protection is the application of advanced electronic signatures. This signature is inserted in the certificate with the Gov.br platform (www.gov.br) that allows the users to sign a document in digital form from their Gov.br account. The document with the digital signature has the same validity as a document with a physical signature.

3.3. Validation

The validation was done in three stages. In the first stage, the compliance with the operational requirements was verified, which were the following: compliance with Table 1, chapter 7.1 (resources) of ISO 9001 [7] and Chapter 7.11 (data control and information management) of ISO 17025 [8].

In the second stage, the developer tests were performed: unit testing to verify that each unit of the code worked correctly (these tests helped identify and correct implementation errors to ensure correct functionality); integration testing to verify that the different components of the software work correctly together; and finally, security testing was performed to identify and correct possible vulnerabilities and ensure that the software is protected against external threats. This involved performing penetration tests, vulnerability analysis, and verifying the security practices adopted.

In the last step, end users performed acceptance testing to verify that the software met their expectations and requirements. This included the execution of specific test cases, simulation of real scenarios, and validation of critical functionalities. Pandora IRTech was tested and incorporated into Labprosaud's quality management system from 2021 to 2023. Since then, a general restructuring in all processes has been observed, especially in the organization and learning at the document level of the quality management system. Figure 3 summarises and illustrates the current structure and features of the created and validated software.

The work faces limitations commonly found in initiatives aiming to digitalize and automate calibration. Key challenges include ensuring the metrological traceability of digital calibration certificates, a strong dependency on robust and interoperable technological infrastructure for cloud integration, and continuous updates to regulatory requirements. For these reasons it is important to note that software validation is an ongoing process and should be iterative between developers and users to ensure that it is working correctly and meeting the changing needs of users.

4. CONCLUSIONS

In summary, the development and use of Pandora IRTech made the management and calibration processes of the laboratory where it was implemented more efficient. Among all the implemented changes, the unification of several spreadsheets in a single software made the records more reliable and efficient.

The results show an innovative approach in the metrology of ionizing radiation and represent a significant advance in improving calibration processes. The combination of 4.0 technologies, such as Artificial Intelligence, cloud computing, data science analysis tools, process automation, and compliance, with the digital calibration certificate standard enables organizations to achieve higher levels of performance and quality.

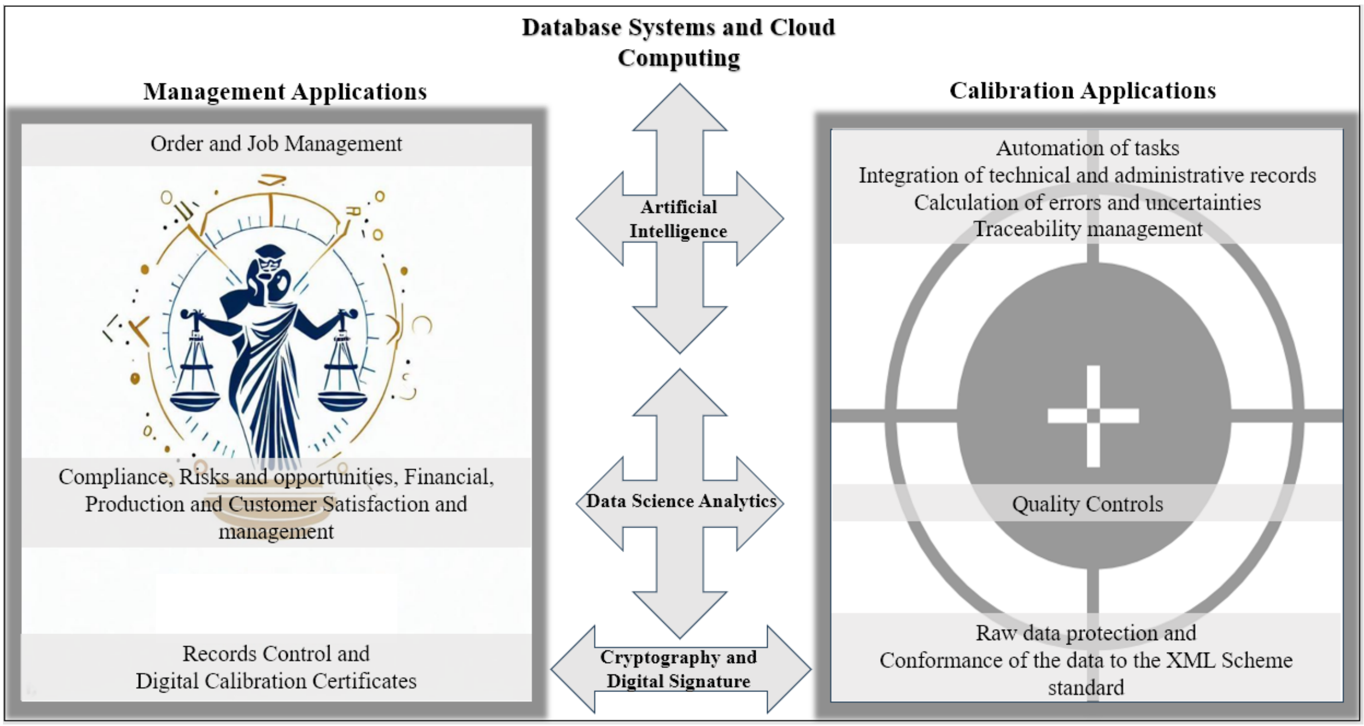

Figure 3. Illustration of Pandora IRTech structure and features.

AUTHORS' CONTRIBUTION

José G. P. Peixoto was the supervisor of the work, Marcus V. T. Navarro was the co-supervisor, Jeovana S. Ferreira assisted in developing the application code, and the others contributed to reviewing the application's code.

ACKNOWLEDGEMENT

The authors acknowledge the National Nuclear Energy Commission (CNEN) for the financial support of this work, and Labprosaud/IFBA, IRD, SBAR, and Ionizing Radiation Technology (IRTech) for the technical support.

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