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Digital Twin and Physical Cyber Systems Applied to Ionizing Radiation: State of the Art in Metrology 4.0

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Abstract: The Fourth Industrial Revolution has brought society many benefits, such as technological advances, and many challenges to be overcome. To increase the synergy between physical and digital systems, most often used in the optimization processes of physical systems, metrology 4.0 has become an essential tool for their development. A state-of-the-art paper is significant in understanding how these applications develop, focusing on Cyber-Physical Systems and Digital Twins in ionizing radiation. The online search was conducted in general and specific databases with keywords in English. Thus, twelve articles were analyzed and discussed, divided into three main themes: indirect applications, ionizing radiation metrology projects, and systematic reviews. It was possible to notice that the number of articles related to these technologies in ionizing radiation is still tiny compared to other areas, especially when compared to the industry, making it even more challenging.

Keywords: Metrology 4.0, Digital Twin, Cyber-Physical System, Ionizing Radiation, Simulation.

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Gêmeos Digitais e Sistemas Ciber-Físicos Aplicados a Radiações Ionizantes: Estado da Arte em Metrologia 4.0

Resumo: A Quarta Revolução Industrial trouxe muitos benefícios à sociedade, como avanços tecnológicos e muitos desafios a serem superados. Para aumentar a sinergia entre sistemas físicos e digitais, mais utilizados nos processos de otimização de sistemas físicos, a metrologia 4.0 tornou-se uma ferramenta essencial para o seu desenvolvimento. Um artigo de estado da arte se mostra relevante para entender como essas aplicações se desenvolvem, com foco em Sistemas Ciber-Físicos e Gêmeos Digitais em radiação ionizante. A busca online foi realizada em bases de dados gerais e específicas com palavras-chave em inglês. Assim, foram analisados e discutidos doze artigos, divididos em três temas principais: aplicações indiretas, projetos de metrologia de radiações ionizantes e revisões sistemáticas. Foi possível perceber que o número de artigos relacionados a essas tecnologias em radiações ionizantes ainda é pequeno se comparado a outras áreas, principalmente em Relação à indústria, tornando-o ainda mais desafiador.

Palavras-chave: Metrologia 4.0, Gêmeos Digitais, Sistemas Ciber-Físicos, Radiações Ionizantes, Simulação.

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1. INTRODUCTION

Nowadays, research, development, and innovation (RDI) in metrology are necessary to support digital transformations and technological advances related to the demands of the Fourth Industrial Revolution (4.0) present in fields such as industry, environment, and health. Several projects have been developed, specifically in ionizing radiation, mainly to "promote the infrastructure of legal metrology to support the processes of conformity assessment and market surveillance" [1]. Studies are being conducted with relevant results in personal dosimetry, digital calibration certificates (DCC), dose prediction in radiotherapy, and clinical imaging using innovative technologies such as Digital Twin (DT), Cyber-Physical Systems (CPS), Artificial Intelligence (AI) among others [2].

CPSs are created through computer simulations to generate virtual environments from physical ones. A calibration laboratory, for example, can be virtualized from its physical characteristics, instruments, and processes, becoming a CPS. The DT is the digital copy of the object, assembly, or processes performed in the real environment, such as calibrating a radiation meter/detector. The software uses AI to produce and obtain data from intelligent sensors/actuators that can: simulate the conditions and technical feasibility of the calibration system; present inferences about its current operational status; intervene due to actuation devices modifying calibration settings; and assist in the production of the digital calibration certificate.

One way to understand real-time DT is to look at it as a dynamic set of digitized data in a time-series format. A property of physical objects is that they exist only instantaneously in the present, with the possibility that, over time, their characteristics will change. It is impossible to go back in time to measure their original parameters. Thus, a DT can repeatedly measure the “still" dynamics at a random point in time. In this way, DT exists simultaneously from the moment the information was collected to the present, significantly expanding the capacity for analyses to be performed [3].

Despite the efficiency gain in lab routine and results for clients, new risks (exclusively from 4.0 metrology technologies) grow from that implantation. They must be considered in developing these solutions and bring the need for control actions [4].

In Brazil, challenges such as measurement systems modernization and the addition of professionals from multidisciplinary fields working in RDI have delayed the transformation process of digital metrology [5]. Moreover, the lack of knowledge of these professionals about metrological applications and calibration results interpretation indicates the need to direct efforts to mitigate such gaps [6].

Thus, to solve new challenges in an increasingly digitized world, public and private organizations are developing applications and infrastructure for digital calibration certificates, researching the comparability between real and virtual measurements, and developing machine learning-based assessment methods associated with artificial intelligence. To support the technical and scientific development of the country, this study aims to present a review based on the analysis of the state-of-the-art digital twin cyber systems applied in ionizing radiation.

2. MATERIALS AND METHODS

To map the state of the art, online searches were conducted in the databases of the International Atomic Energy Agency (IAEA), Scientific Electronic Library Online (SciELO), and Google Academic with keywords defined in the inclusion criteria in English between 20/09/2022 and 03/11/2022.

2.1. Inclusion criteria

Articles, theses, or dissertations published between 2017 and 2022 that are written in English, Portuguese, or Spanish and contain the following keywords:

- “Cyber-physical" systems “Ionizing radiation” and “Digital twin”
- “Computational simulation” and “Digital twin”
- “Digital Twin” and “Monte Carlo”
- "Digital twin” and "calibration" and "metrology" and "PTB"
- "Digital twin” and “review”
- "Cyber-physical system" and "Digital twin" and "metrology 4.0"
- "Ionizing radiation" and "digital twin"
- “Digital twin” and "dose"

2.2. Exclusion criteria

As the search algorithms of the databases provided are imperfect, some findings were excluded from the study. This filtering was performed by consensus of at least five authors after critically analyzing the title and abstract.

2.3. Systematic review

Based on state-of-the-art mapping, a systematic review was carried out to synthesize and discuss the main ideas of the selected scientific documents.

3. RESULTS AND DISCUSSIONS

Table 1 shows the raw search results in numbers. Table 2 presents the selected scientific documents and summarizes their main ideas or contributions. To facilitate understanding, the search results are categorized by application.

Table 1: Gross result

KEYWORDS	IAEA	SCIELO	GOOGLE ACADEMICS
“Cyber-physical" systems “Ionizing radiation” and “Digital Twin”	0	0	27
“Computational Simulation” and “Digital Twin”	0	0	48
“Digital Twin” and “Monte Carlo”	16	0	31
"Digital Twin” and "calibration" and "metrology" and "PTB"	0	0	65
"Digital Twin” and “Review”	1	1	3680
"Cyber-physical system" and "Digital twin" and "metrology 4.0"	2	0	5
"Ionizing Radiation" and "Digital Twin"	0	0	130
“Digital Twin” and "dose"	-	-	989

Source: Survey data conducted on 08/10/2022

Table 2: Selected articles and main idea

TITLE	MAIN IDEA
Development and validation of a CFD-enabled digital twin of a portable HPGe gamma spectrometer. [6]	Development of a system that assists in optimizing the temperature regulation system of an HPGe spectrometer, from simulation data of heat transfer from the environment to the detector and cooler.
Magnetic-Actuated Cyber-Physical System for Interventional Surgery [7]	Creation of a magnetically guided and remotely controlled cyber-physical system that provides more flexible and fast control of invasive surgical instruments from real-time magnetic field calculations.
First steps towards online personal dosimetry using computational methods in interventional radiology: Operator's position tracking and simulation input generation. [8]	A personal dosimetry system based on position tracking with a Kinect v2 system and dose simulation by mount Monte Carlo via MCNP. Validation was performed by comparing with data from personal electronic dosimeters. At the conclusion, the uncertainties associated with the process were estimated, and the results were presented as a framework for developing the online dosimetry system.
A New Cyber-Physical System for Gas Radon Monitoring and Controlling. [9]	CPS and IoT control human radiation exposure—use existing data to deploy sensors for this monitoring.

Virtual Laboratory of Ionizing Radiation Metrology: Validation by Spectrometry [10]	It presents an ionizing radiation metrology laboratory that was virtualized with the proposed development of a Digital Twin, where the critical elements of the laboratory were described in Monte Carlo, using the EGSnrc code with the egs_phd application and had their spectrometry measurements based on N60 radiation quality.
Digital Twin Concepts with Uncertainty for Nuclear Power Applications [11]	Work that presents the application of DT models in nuclear energy, focusing on the description of critical tasks for the quantification of uncertainty in the interaction between physical and digital.
Pitfalls in interventional X-ray organ dose assessment—combined experimental and computational phantom study: application to prostatic artery embolization. [12]	Study of quantification of the influence on the alteration of several parameters in the local dose of X-rays concerning doses in specific patient organs. Using MOSFET dosimeters and reproducing image scenarios, their reconstruction used Monte Carlo simulations exploring the influence of geometric uncertainties, such as the positioning of the patient or the X-ray source, on the dose values in the organ.
The Concept of a Digital Twin of a Radiotherapy System [14]	It addresses the production of a DT for the Russian radiotherapy system KLT-6 to improve the use of users from the use of 3D scanning with virtual reality. These systems are mainly used to maintain and monitor the operating conditions of physical systems and the educational experience.
A systematic review of the literature on Digital Twin: a discussion of contributions and a framework proposal [15]	The authors differ on definitions and use different processes for the construction of a DT, models that seek to represent elements of the real environment, and maybe products and/or processes/services to be a tool for monitoring performance, simulation of scenarios, and source of information for decision making.
Simulation in the design and operation of manufacturing systems: state of the art and new trends. [16]	It is a State-of-the-Art article on Industry 4.0 focused on computational simulation and DT, performing a chronological analysis of the development of these technologies.
Digital twins in manufacturing: An assessment of key features [17]	Four main features have been identified as fundamental to a DT system: digital modeling, support analysis, real-time updating, and automatic control capability.

Source: Authors.

3.1. Indirect applications in ionizing radiation

The study was conducted by looking for ways to minimize heat losses of a HandSpec (High Purity Germanium - portable HPGe) using a DT combined with the Computational

Fluid Dynamics (CFD) method to support the design and optimization of the physical prototype. Simulations were made by JELTSOV et al. [6] to evaluate the relative contribution of different heat transfer mechanisms from the environment to the detector and cooler. The results demonstrate the heat transfer analysis in a cryostat using a heat shield in its vacuum chamber to improve the efficiency of the spectrometer. A detailed mathematical model was built on commercial CFD software (Star-CCM+) according to the manufacturer's CAD (Computer-Aided Design) drawings and design specifications.

SHAN et al. [7] have created a cyber-physical system consisting of two modules: the first, in the patient, is triggered magnetically, and the second is a virtual surgical environment controlled by an operator. This system differs from the others by providing more flexible and fast control of invasive surgical instruments since it uses an algorithm that performs real-time calculations of the magnetic field and how much power is required to move the elements.

The relationship of these studies with ionizing radiation was considered indirect. First, the technology prevents the heat loss temperature regulation system of an HPGe spectrometer, optimizing radiation detection. Second, the system allows surgeons and part of the team to reduce their radiation doses of interventional procedures, considering that they do not need to be at the patient's side.

3.2. Ionizing Radiation Metrology Projects

ABDELRAHMAN et al. [8] have proposed an online personal dosimetry system with many diverse characteristics of cyber-physical systems. Among them is the Monte Carlo simulation (MC) of the environment for estimating the dose by time and position to the source, using the MCNP code and a real-time position tracking system, Kinect, to feed the system of personal dosimetry. He used an electronic personal dosimeter in the operator to compare the results with the online system for validation. The results of the first clinical validation of the system show a difference of about 50% between Hp(10) simulated with MCNP and Hp(10) measured with an electronic personal dosimeter used above the lead apron.

SCARCELLI et al. [9] proposed a cyber-physical system for monitoring and controlling human exposure composed of intercommunicating computer networks. The network is designed to have an intelligent component to connect to physical sensors and their interactions with the external world (communication with the interface system, other sensors in the network, actuator to modify the conditions of the environment). Despite being able to monitor and control different radiation sources, the work was restricted to radon gas. For radiation monitoring, they use a PIN diode.

The article of a laboratory of ionizing radiation metrology was virtualized, proposing the development of a DT, where the critical elements of the laboratory were described in Monte Carlo, using the Code EGSnrc with the application egs_phd [10], and had their spectrometry measurements based on the quality of N60 radiation. According to the authors, the results show a good agreement between the experimental spectra used as a reference in the laboratory and the simulated one. They conclude that the virtual system developed was satisfactory for spectrometry and can be used for other metrological applications.

KOCHUNAS and HUAN [11] address possibilities such as the application of DT models in nuclear energy, the exchange of information between the physical and digital systems, and already-developed tools that can be modeled for nuclear power systems. The article also presents an overview of key tasks for quantifying uncertainty in the interaction between physical and digital.

As demonstrated in his article, there is a greater focus on radiological protection, management, and safety for patients and radiologists. The study aimed to quantify the influence of the alteration of several parameters in the local X-ray dose to evaluate its relevance in the evaluation of doses in specific patient organs. The experiments used MOSFET dosimeters and were conducted by reproducing image scenarios. Their reconstruction used MC simulations exploring the influence of geometric uncertainties, such as the positioning of the patient or x-ray source, on the dose values in the organ. In general, dose values in MC-simulated organs are in accordance with those measured for most cases. Marginal displacements of the X-ray source about simulators lead to deviations from 6 to 13.5% in the dose values of the organ, while the dose in the skin remains relatively constant. Regarding the impact of the composition of the simulator material, the underestimation of dose values in the internal organs is between 12 and 20%, being prevalent throughout the simulation. However, the dose on the skin can be estimated with a low deviation of 1 to 8% for at least two materials. [12]

ZHABITSKII, MELNIKOV, and BOYKO [13] address the use of DT in nuclear power plant (NPP) units in the development of technical systems. NPP must meet stringent safety requirements and can be simulated in training models and analytical and training mathematicians. With this, rectifying the non-conformities revealed in a computational model and not in a real plant is possible, confirming the practical convenience of performing such activity at all project stages. Some possible examples are testing and improving control algorithms; diagnosing the state of technological equipment (pumps, electric motors, pipe valves, etc); examining load monitoring mode programs; and setting up the automatic NPP unit regulators in the commissioning phase in different modes of operation.

ROD'KO et al. [14] address the production of a DT for the Russian KLT-6 radiotherapy system to improve users' use and make it more competitive through 3D scanning with virtual reality. A need for radiotherapy is dose reduction in healthy tissues at irradiation. The structured DT scheme consists of two units: the first consists of sensors to monitor system operating parameters and operating conditions; the second consists of a center for developing, maintaining, and training personnel. These systems are used for the interactive evaluation of the technical status of the equipment in an advanced type of maintenance based on the current state, from the indication of the optimal time for performing the repairs.

3.3. Systematic reviews

ZHABITSKII, MELNIKOV, and BOYKO [13] discuss the problems that arise with the widespread introduction of DT technology for complex engineering objects based on nuclear energy experience. According to the authors, the large number and complexity of the tasks will increase in the future. However, because of its successful solution, we will have a large-scale digital transformation of all walks of life. It is expected that it is necessary to increase the costs of implementing digital technologies to achieve the desired effects of the transformation of industry and the economy. Thus, DTs can significantly increase the pace and efficiency of nuclear power plant construction. At the same time, it is possible to observe certain contradictions with the thesis of the high efficiency of using digital twin technology for all stages of the life cycle of complex engineering objects.

The article is a review that aimed to collaborate with the dissemination of themes related to DT models and sought cost-free means to build and give access to these models to the public. According to the authors, although there is an increasing number of articles in the literature related to DT, there are still several unexplored opportunities and gaps, as well as a vast field for experimentation. Using the (free) Blender, Visual Studio, and Unity programs, the work describes 11 steps that can be used to guide people with programming experience to build a DT applied [15] to the games, noting that with the appropriate adaptations and refinements, these models can be used in areas not yet explored.

The authors investigate the main historical milestones in the evolution of manufacturing systems simulation technologies in industrial approaches. According to the authors, because data is the fuel of the Internet of Things, simulation can facilitate digital integration and give access to digital data for the entire life cycle of a product or process. Thus, the MOURTZIS [16] simulations with DT are an emerging trend, as they can be used to prevent failures in production systems (in the planning phase) and the training of workers (in the training phase) to mitigate safety concerns and improve their efficiency.

ASSAD NETO et al. [17] clear several characteristics of the recent DT models used in manufacturing and then critically analyze with experts in the field to identify which ones are the most significant. The work identifies four main features:

1 – Digital modeling: the ability to generate virtual models that adequately replicate physical, geometric, or behavioral characteristics of physical systems;

2 – Analysis support: the ability to implement analyses to support the delivery of DT services based on physical system data or digital models;

3 – Opportunity update: the ability to update virtual models and data storage platforms in near real-time, parallel to the operation of the physical system;

4 – Control resource: the ability to act autonomously to control the physical system based on analyses performed.

4. CONCLUSIONS

Some crucial findings about indirect applications in ionizing radiation were verified so that they were intentionally highlighted at work. This fact was considered important since the understanding that these are complex systems is improved, and, in most cases, accessory elements can be optimized for the overall improvement of systems, not necessarily restricted to end activities.

A few projects with DT and CPS technologies applied to ionizing radiation were found, and seven were selected for analysis and discussion. Highlights for the online personal dosimetry system are the virtual calibration laboratory and the digital calibration certificate, which are already in more advanced validation stages.

An essential feature of publications on projects and their applied technologies is that, until then, many are restricted to specific applications being developed as particular solutions for the industry, making disseminating information difficult.

Publications of systematic and state-of-the-art are the most found when the theme is DT comprehensively. However, when the application to ionizing radiation is restricted, the number of related articles is significantly lower, with only one publication on use in nuclear energy highlighted. However, it was decided to incorporate three other articles to integrate different technologies that may eventually be applied to ionizing radiation.

Thus, this publication compiles the main findings and becomes an essential tool for aiding the development of studies and projects in metrology 4.0, applied in ionizing radiation.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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