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INTELLIGENT DATA PROCESSING TECHNOLOGIES AS A BASIS FOR MODELING DIGITAL AVATARS IN THE EDUCATIONAL ENVIRONMENT

Objective. To substantiate the conceptual foundations for creating digital avatars in the educational environment based on intelligent data collection and processing technologies. **Methods.** Integration of sensor technologies, IoT, Big Data, machine learning algorithms, comparative analysis of physical and analytical modeling approaches. **Results.** It is shown that combining physical modeling and data analytics enables the development of flexible and adaptive digital avatars reflecting individual user behavior. **Scientific novelty.** The study proves that exclusively analytical models are insufficient and that integrated modeling provides a holistic behavioral simulation. **Practical significance.** The proposed approach can be applied in digital university ecosystems, distance learning platforms, and educational analytics research to enhance personalization and learning efficiency.

Keywords: digital avatar, digitalization, higher education, digital university.

Problem statement. In the conditions of the dynamic digital transformation of the educational environment, the need for new technologies that can provide deep personalization and adaptability of the educational process to the individual characteristics of participants is actualized. A promising solution to this problem is the creation and use of digital avatars – interactive virtual models that can reflect the physical, cognitive, and behavioral characteristics of users, thus providing an individualized approach to learning and interaction in the digital space.

However, despite significant achievements in the field of digital technologies, the scientific basis for the effective combination of methods of physical and mathematical modeling and analysis of large data sets (Big Data) obtained through sensor devices and IoT platforms remains insufficiently developed. This necessitates the scientific justification of the use of intelligent technologies for collecting, processing, and interpreting data, which becomes a prerequisite for the development of effective and functional digital avatars in the modern educational environment.

Analysis of recent research and publications. In recent years, the issue of digital transformation of the educational space has attracted the attention of many scholars and researchers. In particular, the economic and organizational aspects of the implementation of automated systems and digital services were studied in the works of P.V. Huk and O.V. Skliarenko [1], as well as in the research of Y.O. Kolodinska, O.V. Skliarenko, and O.Yu. Nikolaievskyi [2], who considered digital services as the basis of innovative business models, which is close to the use of digital solutions in education.

Digital interactive learning technologies, which form the basis of the modern educational process, are analyzed in detail in the researches of O.V. Skliarenko, S.M. Yahodzinskyi [3], and O.O. Khomenko [4]. These authors emphasize the significant impact of interactive digital technologies on the formation of competencies and personal development of students, highlighting the need for their integration into the modern educational space. At the same time, the socio-cultural aspects of the use of digital technologies and their impact on the formation of new socio-cultural paradigms are considered in depth in the monograph by S. M. Yahodzinskyi [5], where the author substantiates the importance of digital information networks in modern society.

The transformation of the information architecture of universities in the context of digitalization is also revealed in the works of Kubiv S.I. and other authors [11], which analyze the innovative potential and legal aspects of digitalization in European countries, which further confirms the relevance of integrating digital avatars as an innovative solution in education.

Additional context is provided by the researches of A. Kozhyna [10] and H. Lopuschnyak and co-authors [12], which reveal the relationship between inclusive development and digitalization, which contributes to understanding the need for personalization and adaptability of digital solutions, in particular in the educational process, which increases the relevance of the use of digital avatars.

Therefore, the analysis of existing publications shows a significant interest of the scientific community in the implementation of intelligent digital technologies in education, while demonstrating the lack of development of a comprehensive approach that would systematically combine physical and analytical modeling to create digital avatars.

The aim of the article. The aim of the article is to provide a scientific substantiation of an integrated approach to the creation of digital avatars in the educational environment using intelligent data collection and processing technologies, which involves a rational combination of physical and mathematical modeling with the analysis of large sensor data sets. This will ensure maximum adaptability, accuracy, and personalization of the educational process in a digital university.

Presentation of the main research material. A number of scientific researches have been devoted to the evolution of digital avatars (hereinafter referred to as DAs) and the technologies which are the basis for their creation and use. The most common is the concept of four evolutionary stages, which cover the periods from the creation of simple digital models without interactive feedback to modern interactive avatars that exchange information in real time with their physical counterparts or users [6]. It is well known that digital avatars are based on a number of technologies, the development of which directly affects the expansion of the capabilities of these avatars [4, p. 1222]. In the modern educational environment, against the background of the rapid development of the market for educational digital services, it is of particular interest to research intelligent technologies for automating data collection and analysis.

Attention should be paid primarily to the Internet of Things (IoT), Big Data and artificial intelligence technologies, which are responsible for obtaining information about the behavioral and psychophysiological characteristics of users (students, teachers) and creating appropriate adaptive models based on the analysis of this data.

In order for a digital avatar to promptly reflect the state or characteristics of a real person in the educational process, it is necessary to use special sensors and information collection systems integrated into educational platforms. To implement the functions of collecting and analyzing information about user activities, specialized measuring systems consisting of analog sensors and controllers with analog-to-digital converters and data preprocessing tools were developed in the 1960s. After the first processors appeared, such controllers became Programmable Logic Controllers (PLC), which allowed processing information directly on site, as well as quickly changing algorithms for its analysis without making changes to the physical components of the system. This significantly reduced the cost of data collection and analytics processes and facilitated the creation of adaptive user models.

Controllers collected analog signals from various sensors that were directly connected to them. For example, the received signals could be converted to digital format and aggregated with other analog signals. Primary data processing was performed by a digital receiver, which transmitted information to the data collection and analytics server according to the logic of the network protocol. A similar principle was implemented in the systems of supervisory control and data acquisition (SCADA), which were originally used in industry [5, p. 90].

Over time, information transfer technologies have been improving, in particular due to the emergence of Ethernet, which has reduced costs and significantly expanded the ability to process and store information. At the same time, sensors have been improving, and a variety of sensors have appeared that can quickly record a wide range of parameters: temperature, movement, acceleration, touch, atmospheric pressure, humidity, and other physical and behavioral indicators of a person. In addition, the systems of redundancy, optimal location of sensors, as well as algorithms for transmitting, processing, and storing collected information have been improved, which allowed the most efficient use of the data obtained to create accurate models of digital user avatars in the educational environment.

With the development of Internet protocols and wireless technologies such as RFID (radio frequency identification), Bluetooth, and Wi-Fi, and as electronic components become cheaper, data collection and processing technologies have moved from industrial areas to consumer and educational devices. As the demand for intensive data collection and analytics increased, there is a need to scale and standardize data collection processes to ensure prompt access to information for direct users and various analytical applications. The answer to these requirements was the creation of specialized hardware and software platforms of the Internet of Things (IoT) that combine data collection, processing, and analysis into a single system.

The functionality traditionally offered by SCADA systems is now being organically integrated into the broader concept of the Internet of Things, turning individual components of SCADA systems into components of the IoT infrastructure for monitoring and analyzing educational data. The further evolution of such platforms occurred through migration to cloud services. Thus, a modern IoT platform for educational tasks is a set of IT solutions implemented in the cloud environment.

However, it is worth noting that some educational institutions are currently skeptical about placing sensitive data and information platforms in external cloud systems due to information security issues. At the same time, cloud platforms are of increased interest due to much lower restrictions on computing resources and amounts of information storage. In addition, they are able to work with different data models and various information structures, as they support several environments for data development, testing, and analytics at the same time [10, p. 31].

Therefore, an effective IoT platform in the educational environment should have two main characteristics: first, it should be implemented as a hardware and software system for connecting, managing sensors, controllers, and other devices for collecting information about users (students, teachers); second, the platform should provide a wide range of post-processing and analytical functions that take into account the specifics of educational tasks, including modeling digital avatars [1; 5].

In the context of creating digital avatars in the educational environment, it is important to understand the process of collecting and transmitting data through IoT networks. Figure 1 shows a typical data transmission scheme in an IoT network.

As shown in Figure 1, the sensors are placed at control points of the object under study (for example, in the classroom, at the student’s workplace, or in a digital laboratory) and collect data in real time. Each sensor responds to changes in a specific physical or behavioral parameter (temperature, movement, facial expressions, heart rate, etc.), converts this data into a digital format, and transmits it to a microcontroller. The information is then sent to the IoT network, where it is stored and analyzed.

It should be noted that the cost of sensors continues to reduce. According to Microsoft, the average cost of Internet of Things (IoT) sensors has reduced from USD 1.30 in 2004 to USD 0.44 in 2018 [7]. This significant cost reduction has contributed to the widespread implementation of IoT solutions in various industries, including education.

Reducing cost of sensors is one of the key factors driving the growth of the IoT market. For example, according to Precedence Research, the global IoT sensor market is valued at USD 18.34 billion in 2024 and is projected to reach USD 422.13 billion by 2034, at a CAGR of 36.84% [9].

A digital avatar built on the basis of an IoT platform can receive and process large amounts of data, scale according to needs, ensure long-term storage of information, and perform intelligent analytics using machine learning algorithms. This, in turn, allows predicting user actions, optimizing the educational process, adapting learning paths, and increasing the efficiency of interaction with the digital environment.

Leading developers in the field of digital modeling are showing considerable interest in IoT

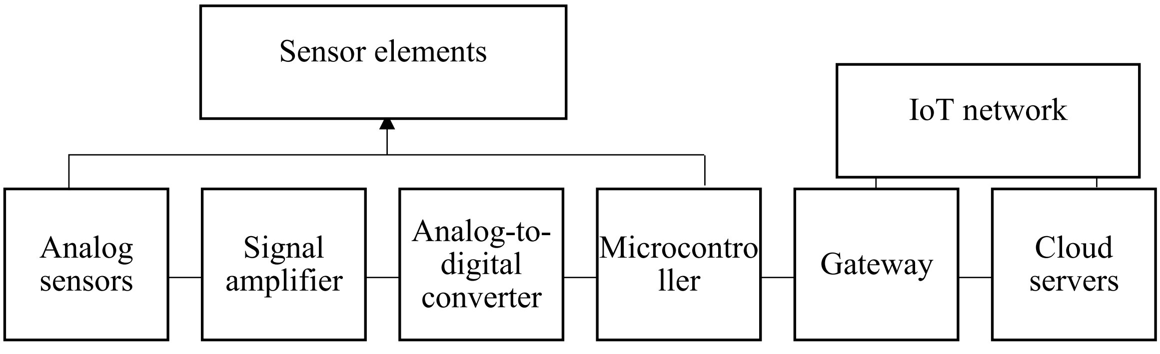

Figure 1. Communication between the sensor and the IoT network

Source: [1;3]

platforms. For example, in 2013, General Electric launched the Predix platform, PTC integrated ThingWorx [8], and the leading solutions in the field of digital IoT services also include Microsoft Azure IoT, AWS IoT, Google Cloud.

It should be emphasized that both big data-based models and approaches based on physical (mathematical) modeling have their strengths and weaknesses (Table 1). There is a widespread belief that the data center approach is simpler: just buy sensors, deploy an IoT platform, and collect large amounts of data. However, big data often turns out to be incomplete, and predicting rare or critical events is difficult.

At the stage when it is necessary to interpret the data collected by sensors in the context of user behavior or the educational process, it becomes almost impossible to recreate a complete picture without a mathematical model. Statistics show that about 95% of the collected data can be redundant, and the process of extracting the meaningful part requires daily highly accurate analytical work [13].

The use of large amounts of data in the process of developing digital models is accompanied by high complexity and significant costs associated with the identification of meaningful patterns and statistically significant correlations. The practical experience of implementing digital modeling projects shows that the amount of data accumulated daily often exceeds the analytical capabilities of available systems, which makes it difficult to effectively process and interpret information.

It is the digital avatar that combines physical modeling with data analytics that allows identifying key observation areas, critical points of interaction, and optimal parameters for collecting information at different stages of the learning process.

At different stages of the digital avatar creation life cycle, the amount of information available varies in both quantity and nature. At the initial stages, such as concept and prototyping, there is no data from a real object because the object itself does not yet exist. During this period, physical or behavioral modeling methods based on theoretical assumptions and simulations are mostly used to build a digital model. With the transition to implementation and practical use, it becomes possible to connect a digital avatar to a real object, which allows the model to be supplemented with experimental data. Later, at the stages of development, maintenance, and operation, the accumulated data plays a key role in the formation of analytical models that allow the digital avatar to be adapted and improved in dynamics, based on the real behavior of the user or system.

The use of different approaches to modeling digital avatars directly depends on the amount of available data about the modeling object and the level of reliability of the mathematical model. In situations where the amount of data is limited, it is advisable to use physical modeling based on theoretical regularities. At the same time, if there is a significant amount of high-quality sensor data, analytical methods, in particular those based on machine learning technologies, can be effective. However, optimal results are achieved by combining mathematical modeling with real-time data analysis, which allows

Table 1

Comparative characteristics of approaches to building digital avatar models

The basis of modeling	Advantages	Requirements/difficulties
Mathematical modeling of physical processes	– Building a model based on physical laws that cover the broad conditions of the object's behavior	– Requires deep knowledge of physical processes
	– Identification of deep cause-and-effect relationships	– Difficulty in creating models for multi-factor systems
	– Precise control of input parameters	– The need for significant computing resources
Analytical approaches / machine learning	– Ability to make predictions beyond the available data	– The need to verify the model based on real data
	– Does not require subject area knowledge, works only with data	– Requires large amounts of high-quality data for learning
	– A flexible approach capable of processing heterogeneous types of information	– Difficulty in interpreting the results (low transparency of algorithms)
	– Good at identifying patterns and relationships	– Does not provide a cause-and-effect understanding of processes
	– Supports adaptability with reinforcement learning methods	– Can only work within the available amount of data, without going beyond the observed experience

Source: [10; 13]

the digital avatar to adapt to changes in the educational environment while maintaining the accuracy of reproducing the user's individual characteristics.

Therefore, the modeling of digital avatars in the educational environment involves the integration of mathematical modeling of physical processes with big data analysis technologies, which ensures a high level of accuracy, adaptability, and personalization. This approach contributes to the formation of intelligently controlled educational systems capable of dynamically responding to individual characteristics of users and transforming pedagogical practices.

Conclusions. The conducted research has shown that the effective creation of digital avatars in the educational environment is possible only if physical and mathematical modeling is combined with big data analytics. This approach allows considering both the theoretical regularities of the modeling object and empirical data obtained from sensor devices and IoT systems, which ensures high accuracy, flexibility, and adaptability of digital avatar models.

It has been established that the use of an exclusively data center approach does not guarantee the completeness of modeling educational interaction, since without a physical or behavioral model, the process of interpreting sensory data is significantly complicated. At the same time, mathematical modeling without empirical support is not able to reflect the individual characteristics of the user. That is why the priority research area is the hybridization of methods focused on the symbiosis of data analytics and structural modeling.

Based on the analysis of modern IoT solutions, information processing technologies, and digital platforms, it has been established that digital avatars can be a key component of an intelligent educational environment. They are able to provide continuous monitoring of educational activity, adapt learning paths to the individual learning style of the user, and support dynamic interaction with other elements of the digital educational ecosystem.

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ІНТЕЛЕКТУАЛЬНІ ТЕХНОЛОГІЇ ОБРОБКИ ДАНИХ ЯК ОСНОВА МОДЕЛЮВАННЯ ЦИФРОВИХ АВАТАРІВ В ОСВІТНЬОМУ СЕРЕДОВИЩІ

У статті розглядається наукове підґрунтя для створення цифрових аватарів в освітньому середовищі на основі інтелектуальних технологій збору та обробки даних. У сучасних умовах цифрової трансформації університетської освіти виникає необхідність у розробці інструментів, здатних забезпечити персоналізацію навчального процесу, динамічну адаптацію освітніх ресурсів до потреб користувачів, а також інтелектуальну взаємодію у цифровому просторі. Одним із таких інструментів є цифровий аватар – віртуальна модель особи, що може імітувати фізичні, когнітивні та поведінкові характеристики студента чи викладача. Основна увага у дослідженні приділена питанням інтеграції сенсорних технологій, Інтернету речей (IoT), Big Data та алгоритмів машинного навчання як основи для побудови цифрових аватарів нового покоління. Проаналізовано етапи розвитку цифрових технологій, починаючи від промислових систем контролю та збору даних (PLC, SCADA) до сучасних IoT-платформ з хмарною обробкою, які використовуються в освітньому середовищі. Показано, що зниження вартості сенсорів та доступність IoT-рішень сприяють поширенню технологій моделювання поведінки користувача в реальному часі. У статті наголошено, що ефективне створення цифрових аватарів вимагає поєднання двох підходів – фізико-математичного моделювання процесів та аналітики даних, отриманих від користувачів. Проведено порівняльний аналіз обох підходів, їх переваг та обмежень. Доведено, що виключно аналітична модель не забезпечує цілісного уявлення про поведінку об’єкта, а лише у поєднанні з фізичною моделлю дозволяє сформувати гнучку, точну і адаптивну структуру цифрового аватара. У результаті дослідження сформульовано концептуальні засади побудови цифрових аватарів як складових інтелектуального освітнього середовища, які здатні не лише відображати індивідуальні особливості студентів, але й прогнозувати їхню поведінку, адаптувати освітні сценарії та підвищувати ефективність навчального процесу загалом. Запропонований підхід може бути використаний у рамках цифрових університетських екосистем, платформ дистанційного навчання, а також у дослідженнях адаптивного навчання, цифрової педагогіки та освітньої аналітики.

Ключові слова: цифровий аватар, діджиталізація, вища освіта, цифровий університет.