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Formation the Robotic Mechanism Digital Twin Structure

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Abstract
The paper is devoted to solving the current socio-economic and ecological problem of developing mechanisms for the possibility of remote determination of radiation parameters and handling materials in conditions of significant radiation. Robotic mechanisms used in dangerous areas have a certain resource, and the execution of planned operations requires trouble-free operation of component systems. These are systems that are primarily critical for management. In this regard, it is very important to protect them and reduce maintenance costs. One of the methods that has already proven itself from the positive side in nuclear power is the use of a complex of interconnected digital twins that allow individual predictions to be made for each piece of equipment in a complex system. Problems in work can be detected in real time, and the approach based on a digital twin allows you to avoid breakdowns and monitor the degradation of systems. The development involves both new approaches in creating digital twins, as well as the experience of previous theoretical and experimental research conducted by the authors of the project. The research results will allow for the first time to create competitive domestic complexes that are able to extend the service life of equipment critical for ensuring human safety.

INTRODUCTION

Robotic mechanisms, which are used to work with radioactive and radiation-contaminated materials in the conditions of radiation and nuclear accidents accompanied by significant radiation, belong to the direction of research from the list of priority topics for solving the problems of defense, security, economy and society of Ukraine. Robotic mechanisms when operated in aggressive conditions receive damage that shortens the service life of component systems and the mechanism as a whole. The uninterrupted operation of such safety-critical mechanisms is an important problem, the solution of which is aimed at the research of the authors of the project. The solution to the problem is supposed to be solved thanks to the parallel simulation of digital twins of critical importance for the functioning of the component systems of robotic mechanisms and the complex analysis of data obtained from the individual forecasts of each digital twin. Such simulations can be performed both for new equipment samples and for those that have been in use for a long time.

The nuclear industry and radiation hazardous environments are best suited for simulation because there are many things that cannot be physically verified. The resulting solutions, oriented in the project to specific goals, will be useful for use by the rest of the industry with appropriate adaptation.

The proposed work is based on the authors' previous theoretical and experimental research related to the development of machine learning and artificial intelligence systems in the optimization of parameters of electromechanical systems and digital twins of electromechanical and electrical power objects based on the ANSYS Twin Builder software. Regarding robotic systems and the reliability of the nodes of industrial executive mechanisms, numerous studies were conducted by the project manager and authors, including comprehensive studies of digital twins based on reduced-order models for such objects. According to the results of the research of digital twins and artificial intelligence systems, experimental samples were created and tested in the O.M. Beketov National University of Urban Economy in Kharkiv laboratory.

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Scientific and technical research on the implementation of digital twins determines a number of the most priority areas of modern energy, electrical engineering, heavy industry and robotic systems [1, 2]. The work of domestic authors [3, 4] is dedicated to the methodology for the development of digital twins in industry and the economy. In paper [3] the issues of reliability analysis during operation of digital twins are revealed. The paper [4] is devoted to the general methodology for the construction of digital twins and the methods used when combining the socio-economic sphere and technologies. In [5], the issues of using digital twins of robotic complexes in industry, as well as the implementation of artificial intelligence algorithms in such systems, are discussed. The paper [6] provides detailed information on the implementation of digital twins in nuclear power using ANSYS Twin Builder software and ANSYS Digital Twin technology. This paper describes the experience of ANSYS in implementing a digital twin of a nuclear power plant and predicting the life of equipment and safe modes of operation. The work of authors from the USA [7] is devoted to the development of digital twins of robotic mechanisms for critical infrastructure and security facilities. The use of digital twins of technical objects to analyze their reliability indicators is presented in papers [8, 9]. A promising direction in the introduction of digital twins is the combination of simulation of work processes with the presentation of analysis results in the form of augmented reality [10], which significantly improves the quality of feedback with the object of research. Analysis of the results of research by domestic and foreign scientists allows us to distinguish three formed categories: (a) the methodology of digital twins, separated from specific objects; (b) digital twins of macro objects; (c) digital twins of individual nodes of complex objects.

Given the deep state of research on the issue of creating and using digital twins, we can conclude that there are objectively all prerequisites for reproducing such a leading technology for specialized tasks. In addition, the presence of a large number of modern studies and the corresponding implementation of the results indicates the relevance of digital twins and their orientation to increase the efficiency, economy and versatility of production or other areas of application. However, there are open issues of combining a number of digital twins of one object into a single system and organizing communication between them; combination of augmented reality and feedback from the simulation of digital twins, development of models of specialized fields of application; introduction of machine learning and artificial intelligence in the model of digital twins; adaptation of specialized software to practical application, etc.

In this regard, the implementation of an approach based on high-performance digital twins to increase the safety, reliability and fail-safe use of robotic mechanisms in dangerous and aggressive environments is of primary importance to ensure the possibility of human-safe remote determination of parameters and handling of materials in conditions of radiation.

The results of the analysis of the current state of research of robotic and remote-controlled mechanisms, which work in environments with increased radioactive danger or radioactive materials, indicate the absence of flaws in the assessment of their technical condition during operation. The implementation of the technology of digital twins [1], which work in real time in conjunction with a real object, is considered for the first time.

Known works on the use of digital twins in robotized mechanisms [2, 5, 7] are focused on the development of systems based on the principle of "sensors - model - visualization" and are devoted to solving the issues of autonomous behavior of robotic systems and making independent decisions by them. In the project presented for consideration, on the contrary, the operator of robotic mechanisms makes decisions about their behavior, but receives real-time information about their current state.

In papers [3, 4] and similar ones, the processes of creating digital twins are considered purely using both specialized software and own software codes. This project is not dedicated to digital twins - this modern approach is considered no more than an effective tool for solving the urgent problem of ensuring the reliability of the functioning of robotic mechanisms in difficult conditions [6], which is being solved for the first time.

Augmented reality systems [10] often accompany both technological processes and demonstration samples. The authors of the project for the first time combine the visualization of the state of robotic mechanisms compatible with data that comes in real time from digital twins. This approach will significantly increase the efficiency of the operator's work and will serve as an additional precaution to ensure the safety of handling in conditions of radiation contamination.

A series of papers [3–4, 8, 9] and similar ones are devoted to issues of implementation of the methodology of evaluation of the simulation of digital twins, predictive analytics, optimization, etc. Such materials significantly help solve the problems posed in this research work, however, the authors, in contrast to existing works, for the first time solve the complex task of monitoring the reliability and time of trouble-free operation of a complete mechanism based on the analysis of the state of a number of interconnected digital twins of individual nodes. In addition, such research is accompanied by new solutions in the implementation of machine learning algorithms, artificial intelligence and methods of determining reliability indicators, based on an integral assessment of the state of the virtual analogue and the real mechanism that corresponds to it.

The aim of the research work is to develop methods and means for creating digital twins of robotic and remote-controlled mechanisms that work in radioactively dangerous conditions, ensuring their trouble-free operation

THE APPROACH TO FORMATION OF ROBOTIC MECHANISMS STRUCTURE

When using robotic and remote-controlled mechanisms in environments of increased radiation, both the internal equipment of the mechanism and its external parts gradually lose their efficiency [10]. Because of this, a situation can arise and, as practice shows, occurs when such mechanisms fail directly during use. Such cases are critical for safe handling in the zone of radiation contamination or when working with radioactive samples, because the communication with the operator is interrupted, which makes it impossible both to assess the current state of danger and to perform certain operations provided for by the procedure for handling radioactive materials. The idea of the work is to develop such a system that would be able to analyze the readings of devices and sensors in real time during the operation of robotic mechanisms and perform predictive simulations of the current state of the equipment, the period of trouble-free operation, and provide warnings about dangerous modes of operation that may occur in the short term perspective In addition, such a system is scalable and can go beyond the analysis of the internal state to the analysis of the hazardous state of the environment. The development of such a system is envisaged using the technology of digital twins, which are able to use real data to check the condition of a real object based on its virtual counterpart. This approach will make it possible to determine indicators that cannot be determined in real physical conditions. For example [11–13], if you need to know whether an expensive robotic complex can break its operating mode, then in reality it is impossible to do without destroying it, but it can be simulated. In turn, this approach requires the development of not one, but a number of digital twins of individual components, which as a whole form a complete mechanism. The number of such twins depends on the existing systems and can reach dozens in relatively simple objects and tens of thousands in the simulation of industrial enterprises. An additional optional task is the integration of an augmented reality system for a better perception by the operator of the current state of the equipment and the environment. In this regard, an important scientific and applied task is the development of complexes based on digital twins to perform new specific functions for determining the state of operation of the equipment and its predicted behavior, including with the involvement of machine learning algorithms and artificial intelligence [14–16].

DIGITAL TWIN REALIZATION IN ANSYS TWIN BUILDER

The software and hardware part of the development of the complex is based on the use of approaches to design and simulation, which are used by the world's leading companies and have positive experience in the implementation of digital twins in nuclear energy. The most modern approaches and licensed software complexes, such as ANSYS Twin Builder, ANSYS Digital Twin, Azure Digital Twins and augmented reality environments, will be used to implement all components of the project [17-20].

Use the ANSYS Static ROM Builder to create a Reduced Order Model (ROM) which reconstructs in real time an accurate approximation of solver solution fields for any set of parameter values. The ROM is built from a set of parameterized converged field solutions from any solver. ROM input parameters can be scalar or field parameters, and can be based on either physical parameters (for example, material properties or boundary conditions) or shape parameters. These input parameters are defined during the design of experiments and managed during simulation.

Static ROM Builder [21–25] can also be used on transient simulation results in a context of a "parametric field history": it requires that the simulation of each design point is made on the same fixed time grid. In this case the snapshot is the assembly of the field results at each timestep.

The first part of constructing a ROM consists of building a basis of vectors representative of any field solution X within the design space.

A Singular Value Decomposition (SVD) algorithm extracts this basis from the learning data. If M is the matrix composed of the learning data (n learning snapshots) in which each column represents the values of each individual snapshot, the SVD of the M matrix can be written as:

$$M = U \cdot \Sigma \cdot V^{*},$$

$$M = [\vec{s}_0 \quad \vec{s}_1 \quad \dots \quad \vec{s}_n] = [\vec{u}_0 \quad \vec{u}_1 \quad \dots \quad \vec{u}_n] \times \\ \times \begin{bmatrix} \sigma_0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_n \end{bmatrix} \times [\vec{v}_0 \quad \vec{v}_1 \quad \dots \quad \vec{v}_n],$$

where s_i are the learning solution vectors (n learning snapshots, where n is generally smaller than the snapshot size); Σ is a diagonal matrix composed of σ_i the singular values of matrix M; U and V are unitary matrices: $U \times U^* = I$ and $V \times V^* = I$; U and V are composed of the left singular vectors $\overrightarrow{U_i}$ and the right singular vectors $\overrightarrow{V_i}$ of M respectively.

From the mathematical properties of the SVD, the M matrix can be approximated by a linear combination of the first r left singular vectors with $I = 0, \dots, r$ $(r \leq n)$. These vectors will be referred to as modes. The basis of the r modes is the optimal basis of rank r to approximate M. The accuracy (Fig. 1) of this approximation is given by

$$RMS_{error} = \frac{\|M - M_r\|}{\|M\|} = \sqrt{\frac{\sum_{i=r+1}^{n} \sigma_i^2}{\sum_{i=1}^{n} \sigma_i^2}},$$

where M_r is the projection of the M matrix in the basis of r modes; the norm used in this equation is the Frobenius norm.

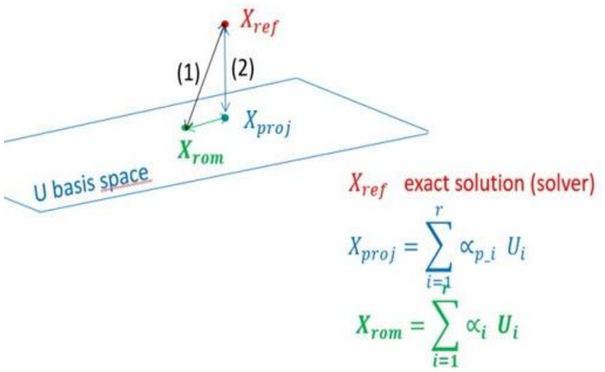

Figure 1. Description of the approximation error

The field solution X in the design space can then be approximated as a linear combination of these r modes as shown in the following equation

$$X = \sum_{i=1}^{r} \alpha_i U_i.$$

For small r values, these two projection errors are almost the same, meaning that the corresponding modes represent a snapshot outside of the learning set as well as they do the learning set itself. When r increases, the difference between the two errors increases (see figure below), meaning that the corresponding modes are not fully converged: they better represent the learning set than they do an outside snapshot. Based on this separation point, an optimal number of modes r is proposed. In this example (Fig. 2), we see that the optimal number is approximately six. For higher r values, the projection error for solution vectors left out in the “Leave One Out” process does not decrease any further (green curve stable).

Selecting the Embed Geometry option embeds the geometry within the exported ROM component. This allows for real-time visualization during Twin Builder simulations [26–30] using the Ansys Stand Alone ROM Viewer (Fig. 3).

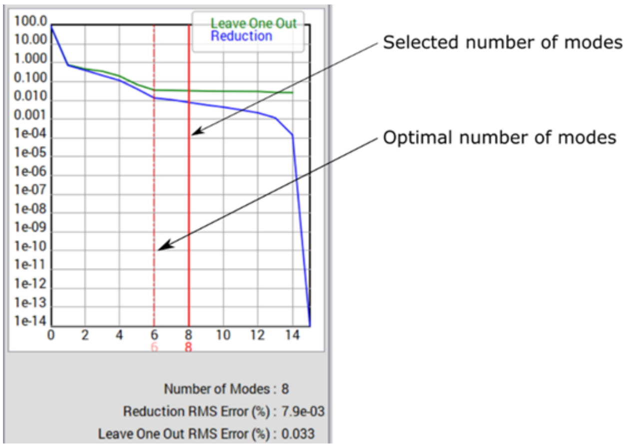

Figure 2. Diagram for define the optimal r mode number

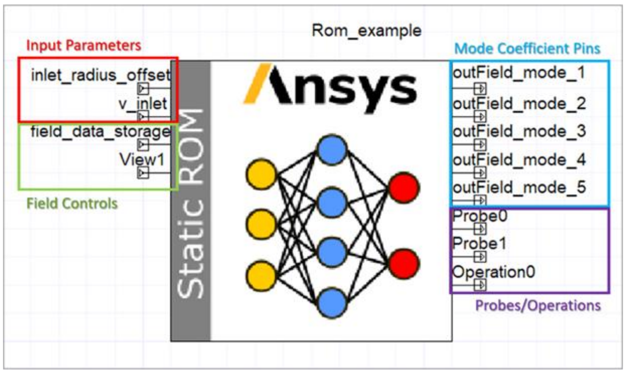

Figure 3. An example of ROM object in Twin Builder

As mentioned previously, output pins consist of mode coefficient pins and pins corresponding to probes and operations (previously defined and enabled). Input pins correspond to the parametric inputs of the model. In addition, a **field_data_storage** pin and **view%i%** pins might be available, discussed in more detail below.

A Static ROM Component is capable of storing field data in various ways using a combination of internal parameters (see figure below) and the aforementioned pins. The storage location is determined using the **writing_location** parameter [31].

These properties correspond respectively to the simulation end time, the minimal timestep and the maximum timestep. The schematic should look similar to the one shown below (Fig. 4). Having set up the ROM inputs, The simulation settings should also be defined by clicking the Analysis/TR icon located in the Project Manager pane. The properties should be specified as T_{end} = 20 s, H_{min} = 0.1 s and H_{max} = 0.1 s. Lastly, set-up a graph to display the data from the probe and operation pins by using the **Results** section in the Project Manager (see Generating Reports and Postprocessing).

This will calculate and provide the results similar to those shown on Fig. 5. The values for Point0 are dependent on the probe location and might differ.

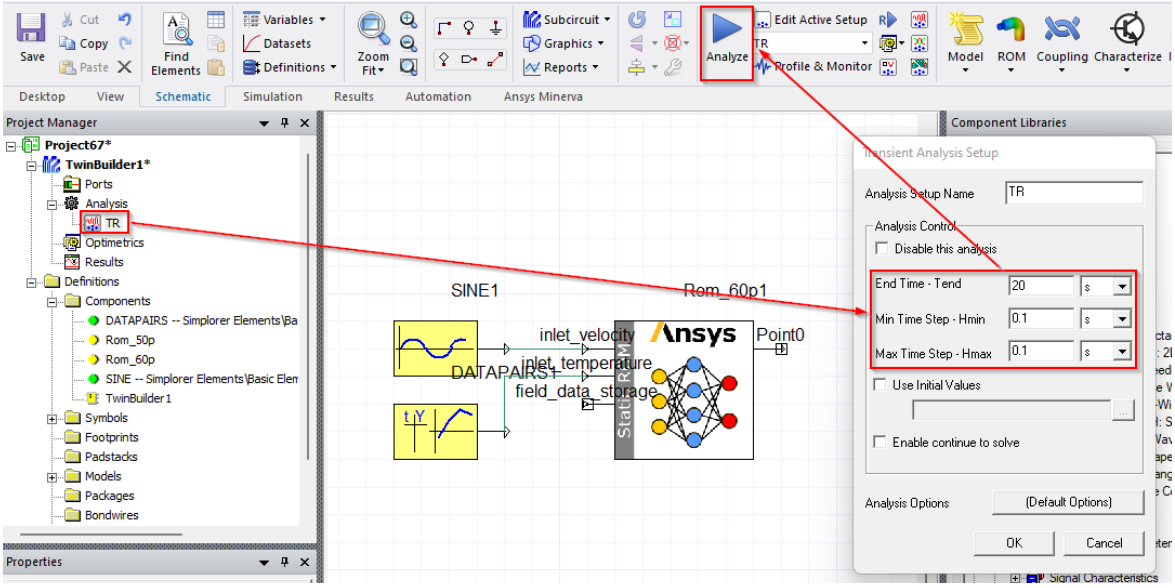

Figure 4. Formation of digital twin model in ANSYS Twin Builder

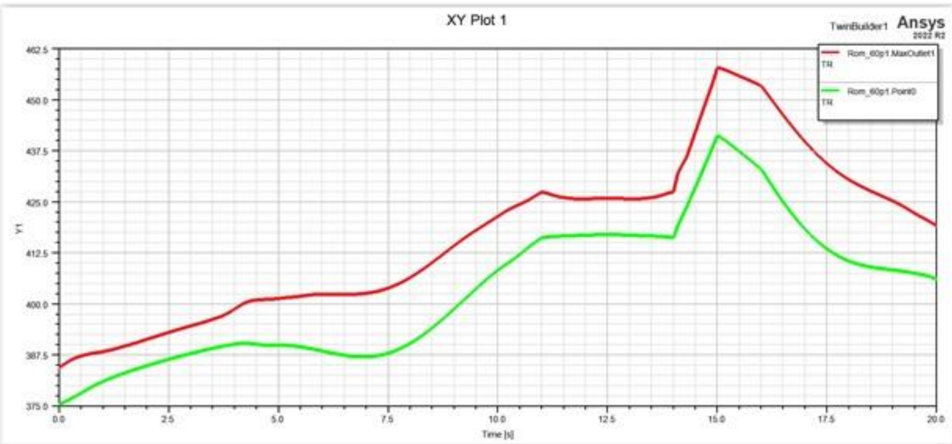

Figure 5. Simulation results of a digital twin (probe location point)

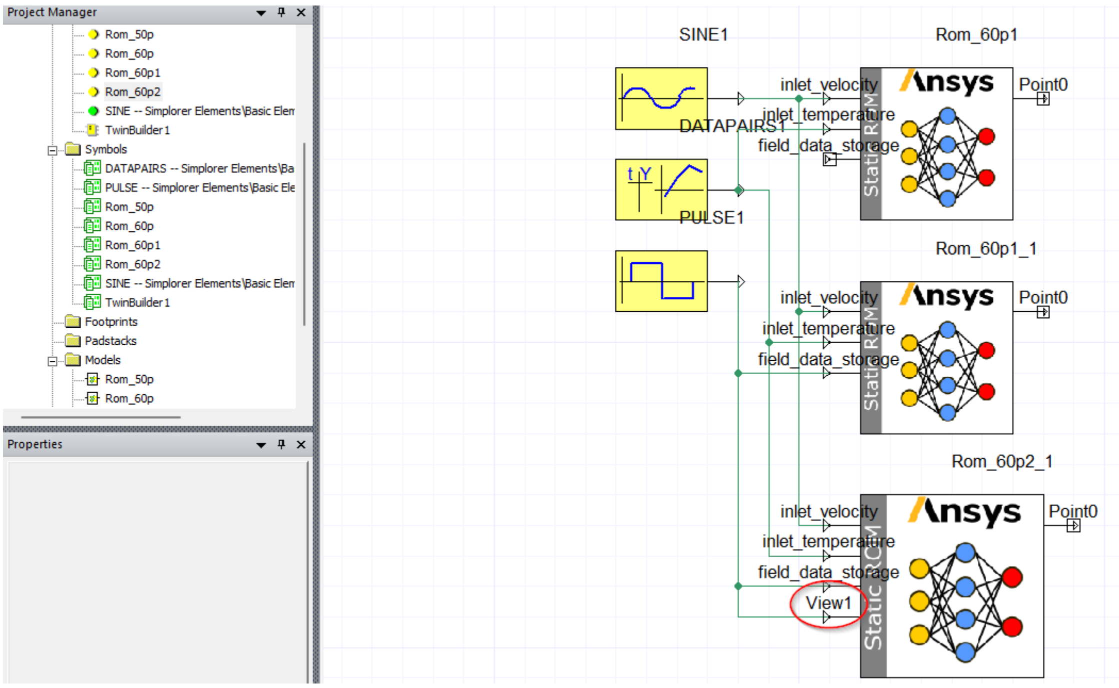

Figure 6. Complex digital twin model structure

The new ROM component (Fig. 6) has an additional parameter: **LaunchViewer**. Twin-click the component and set **LaunchViewer** to **1**. During analysis, the StandAlone ROM Viewer will start automatically. When opening the **ROM_60p2** component parameters, new properties appear. These new parameters are linked with the visualization capability and are self-explanatory. Disable the viewer launch and keep everything else at its default.

Lastly, the option **Add mode coefficients output pins** allows for export with exposed mode coefficient pins. This functionality can be used for more advanced purposes and to create custom functionality. The exposed pins can for instance be used to define twins for ROM-to- ROM or ROM-to-Solver couplings.

DIRECTIONS OF CREATION DIGITAL TWIN MODELS

The paper is based on the authors' previous research in the development of digital twins of electrotechnical and electric power objects, software complexes for optimizing the parameters of electromechanical devices based on machine learning using artificial intelligence algorithms. Digital twins are not the purpose of this work, but the specifics of their construction, the synthesis of a complete structure of a virtual analog from individual components is used as a basis for the development of a system for real-time analysis of the serviceability and the period of trouble-free operation of robotic and remote-controlled mechanisms that work in environments with increased radioactive danger or radioactive materials. In such aggressive conditions, the equipment works in extreme conditions and can suddenly fail, which is unacceptable for this category of application. The combination of the technology of digital twins with a real mechanism will make it possible to predict emergency situations in a timely manner and to warn the operator in advance about the danger, which will provide the possibility of remote determination of parameters and handling of materials in conditions of radiation that is safe for humans.

The idea of the work consists in the development of a fundamentally new ideology to ensure the safety of operation of robotic and remote-controlled mechanisms used in dangerous zones of increased radiation, which is based on timely warning of the operator thanks to the real-time functioning of a virtual analogue of the mechanism (otherwise, a digital twin). Such a virtual system is capable of assessing the danger based on the readings of sensors, predicting the service life of both individual nodes and the mechanism as a whole, and simulating physical phenomena that are fundamentally impossible to measure or reproduce in laboratory conditions. The functioning of such a system is based on the use of not one, but a number of digital twins according to the principle of a separate twin for each critically important node of the mechanism. The prediction of danger and the state of operation of the mechanism is carried out with the support of machine learning technology and artificial intelligence algorithms. In addition, the operator has increased immersion in the processes taking place due to the introduction of augmented reality technology, the data for which is transmitted by a complex of digital twins. Thus, ensuring the reliable operation of robotic mechanisms in conditions of radiation danger is achieved through the use of a set of measures. The developed solutions to the specified scientific and technical tasks are relevant not only for the specified field of use, but also in the future for other fields and are based on the previous works of the authors, domestic and foreign scientists. and the equipment required for their implementation will be discussed.

CONCLUSIONS

Implementation of the development will make it possible to produce in Ukraine modern systems for analyzing the reliability of robotic and remote-controlled mechanisms that work in environments with increased radioactive danger or radioactive materials compatible with the monitoring of their work by a connected virtual analog - a complex of a number of digital twins. Thanks to this, the results of the work will contribute to solving the following important domestic and global socio-economic and environmental problems.

1. Increasing the reliability of the operation of robotic and remotely controlled complexes in the conditions of a radioactive environment, the functional purpose of which is to provide timely results of observation and analysis of harmful substances, assessment of the state of the environment. Trouble-free operation of such mechanisms is critical for ensuring human safety during remote determination of parameters and handling of materials under radiation conditions.

2. Development of the high-tech industry sector and promotion of the creation of new jobs due to the production in Ukraine of domestic software modules of digital twins, modules for expanding their functional capabilities in the direction of specialized operation, scaling the obtained solutions to other sectors of industry and the national economy.

3. Increasing the export potential of the country due to the implementation of the reliability control methodology of robotic complexes and remotely controlled mechanisms compatible with the technology of digital twins. Extension of developed solutions to the Internet of Things sector and implementation of augmented reality in the routine work of operators of complexes that are managed remotely.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

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Формування комплексного цифрового двійника роботизованого механізму

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Анотація. Робота присвячена вирішенню актуальної соціально-економічної та екологічної проблеми розробки механізмів можливості дистанційного визначення радіаційних параметрів та поводження з матеріалами в умовах значного радіаційного випромінювання. Роботизовані механізми, що використовуються в небезпечних зонах, мають певний ресурс, а для виконання запланованих операцій потрібна безаварійна робота складових систем. Це системи, які в першу чергу критичні для управління. У зв'язку з цим дуже важливо захистити їх і знизити витрати на технічне обслуговування. Одним із методів, який уже зарекомендував себе з позитивного боку в атомній енергетиці, є використання комплексу взаємопов'язаних цифрових двійників, які дозволяють робити індивідуальні прогнози для кожної частини обладнання в складній системі. Проблеми в роботі можна виявити в режимі реального часу, а підхід на основі цифрового двійника дозволяє уникнути поломок і стежити за деградацією систем. Розробка передбачає як нові підходи до створення цифрових двійників, так і досвід попередніх теоретичних та експериментальних досліджень, проведених авторами проекту. Результати досліджень дозволять вперше створити конкурентоспроможні вітчизняні комплекси, здатні подовжити термін служби критичного для забезпечення безпеки людини обладнання.

Ключові слова: Складна структура; Модель ROM; Моделювання перехідних процесів; Digital Twin; Twin Builder

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