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The concept of twin digital models as support for production and service processes of technical facilities

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Abstract. The article presents the concept of using twin digital models as support for production and service processes of technical facilities. The implementation of the concept can be helpful in diagnostic processes and proactively diagnose the condition of technical objects in real time and report actions to ensure the continuity of processes. The concept assumes the creation of a digital model of a technical object for the purposes of improving the operation processes of the machine park (means of transport, means of production). A comprehensive and integrated solution will improve work efficiency and lower service costs.

Keywords. mathematical model, diagnostics, prediction, exploitation

1. Introduction

In recent years, many scientific papers have been published that present various applications of digital twins (DT) for technical objects. The most important papers include [1,2,5,11,12]. All of the above papers highlight the potential of digital twins (DT) to improve the performance, reliability, and safety of technical objects. DT can be used to monitor the state of objects in real time, simulate their behavior, and optimize their performance. DT offer a number of advantages over traditional methods of monitoring and managing technical objects. DT can be used to monitor the state of objects in real time and identify potential problems before they occur. This can help to improve the performance and reliability of objects. DT can help to reduce the costs of maintenance and repair of objects. With DT, problems can be identified and repaired more quickly, which can extend the lifespan of objects and reduce the cost of their maintenance. DT can be used to monitor the state of objects for potential safety hazards. This can help to prevent accidents and failures. DT also have some limitations. DT can be expensive to implement and maintain, and require access to large amounts of data.

The concept assumes the creation of a digital model of a technical object for the purposes of improving the operation processes of the machine park (means of transport, means of production). A comprehensive and integrated solution will improve work efficiency and lower service costs. For the purposes of the concept, a technical object in the sense of a device performing work is characterized by quality. According to the ISO8402 standard, it is a set of properties and numerical characteristics of a product or service that affect its ability to meet needs. Quality depends, among other things, on operation and handling.[7]

Analyzing selected publications, it can be stated that Digital Twins (DT) are virtual representations of physical infrastructure assets [1] that can be used for monitoring, diagnostics, forecasting, and optimizing their performance. DTs can help improve the efficiency, reliability, and safety of infrastructure assets, as well as reduce maintenance costs. There are various types of digital twins that can be used to manage different types of infrastructure assets such as roads, bridges, buildings, and energy networks. Digital twins are created based on data collected from physical infrastructure assets. This data can come from various sources, such as sensors, measuring devices, and telematics systems. The data is then processed and analyzed to create a virtual model that reflects the physical state of the asset.

DTs can bring many benefits to infrastructure management. They can help improve performance - DTs can be used to optimize the operation of infrastructure assets. For example, they can help identify areas where performance or efficiency can be improved. They can be used to increase reliability - DTs can be used to monitor the condition of infrastructure assets. For example, they can help detect potential faults before they occur. They contribute to enhancing safety - DTs can be used to identify potential threats to the safety of infrastructure assets. For example, they can help develop emergency plans. This action translates into reduced maintenance costs - DTs can help reduce the maintenance costs of infrastructure assets. For example, they can help in planning repairs and maintenance. There are many different types of digital twins that can be used to manage various types of infrastructure assets. They can be used to monitor the condition of roads and identify potential threats, such as potholes or surface damage. To monitor the condition of bridges and identify potential threats, such as corrosion or structural damage, as well as buildings and energy networks.

There is also a concept [2] that DTs can be used as virtual representations of cities that can be used for simulating and predicting various scenarios for city development. City DTs can help make better decisions regarding urban planning, transportation, energy, and other areas of city management. City DTs can also be used to engage the community in the decision-making process regarding city development. A digital twin of a city is created based on data collected from various sources such as:

- Geospatial data, such as maps, aerial photos, and satellite data.
- Demographic data, such as population, income, and employment data.
- Environmental data, such as air and water pollution data.
- Traffic data, such as road and public transportation data.
- Infrastructure data, such as building data, energy and water networks.

This data is then processed and analyzed to create a virtual model that reflects the city's state. City DTs can bring many benefits to city management. They can help improve urban planning - City DTs can be used to simulate different scenarios for city development. They can, for example, help identify areas where public transportation accessibility can be improved or balance city development. Further benefits may include improving transportation efficiency and energy savings. They can also be used to track crisis situations such as fires or floods. For example, New York uses DTs to simulate various scenarios for city development, such as climate change or population growth. London uses DTs to improve the efficiency of public transportation. Singapore uses DTs to monitor air and water quality. Tokyo uses DTs to engage the community in urban planning processes.

DTs find wide applications in industry [5], such as in production, machine and equipment maintenance, supply chain management, and production process optimization. DTs can be used to simulate the production process and identify potential problems. They can, for example, help identify areas where material or production processes can be improved. It is interesting to use them to monitor production performance and identify areas where it can be improved. They can, for example, help identify areas where material or energy consumption can be reduced. Currently, Siemens uses DTs to monitor factory performance and identify areas where it can be improved. General Motors uses DTs to simulate the production process of cars and identify potential problems. Caterpillar uses DTs to monitor the condition of machinery and equipment and identify areas where maintenance is required.

In publication [7], a diagnostic model is presented that can be used to detect faults in complex technical objects. The model consists of three main modules:

- Data collection module - collects data from sensors and devices installed in the object.
- Data analysis module - analyses data collected by the data collection module to detect anomalies.
- Diagnosis module - determines the type and location of the fault.

The model can be used for various types of technical objects, including vehicles, machinery, and industrial equipment. In publication [8], the application of a digital twin for diagnosing faults in rotating machinery in the intelligent industry is presented. A digital twin is a virtual representation of a physical object that can be used for monitoring, diagnostics, and predicting its state. The model has been implemented and tested on the example of rotating machinery. Tests showed that the model is able to detect most of the faults occurring in the machine, including engine faults, drive system faults, and bearing faults. This has led to the presentation of the idea in this article.

Therefore, it is advisable to monitor these processes to avoid downtime and unplanned failures. For this purpose, it seems reasonable to develop a system for predicting equipment failure, monitoring the current wear of components. The solution could be based on the infrastructure of measurement sensors and prediction algorithms. The proposed system should be able to detect and report incorrect operating modes of devices in the predictive model before the occurrence of states indicating their failure. Pre-failure (with failure symptoms), failure and degraded operation correspond to different patterns of abnormal operation. The algorithm of the application concept of twin digital models as support for production and service processes of technical facilities show fig. no. 1.1.

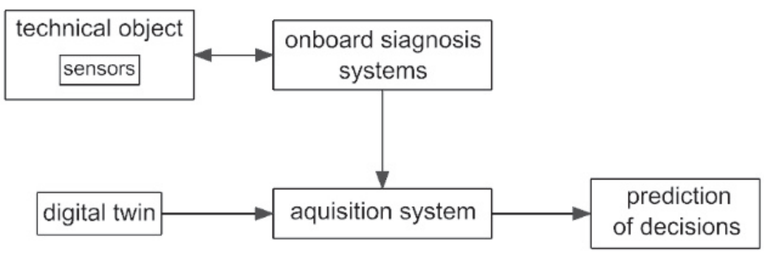

Figure 1.1. The algorithm of the application concept of twin digital models as support for production and service processes of technical facilities

The diagram illustrates the algorithm for applying the concept of digital twins to support the production and servicing processes of technical objects. This algorithm consists of four steps:

1. Creation of a digital twin of the technical object: In this step, data is collected from the object using sensors, cameras, and other devices. This data is then used to create a virtual model of the object that accurately reflects its physical state;

2. Monitoring of the production and servicing processes of the technical object using the digital twin: In this step, the digital twin is used to track the object's performance in real-time and identify potential issues. For example, the digital twin can be used to monitor the flow of materials through the production process or the condition of machinery and equipment;

3. Simulation and optimization of the production and servicing processes of the technical object using the digital twin: In this step, the digital twin is used to simulate different production and servicing scenarios and identify the most efficient and effective processes. For example, the digital twin can be used to simulate the impact of different machine settings on production efficiency or the effect of various maintenance schedules on equipment reliability;

4. Decision support in the production and servicing processes of the technical object using the digital twin: In this step, the digital twin provides real-time information to decision-makers about the object's performance and potential issues. This information can be used to make better decisions regarding the operation and maintenance of the object.

Each step of the algorithm can be implemented using various tools and technologies. For example, a digital twin can be created using computer-aided design (CAD) software or building information modeling (BIM) software. It can be monitored using various sensors and devices, such as temperature, pressure, and vibration sensors. The digital twin can be simulated and optimized using different simulation software packages.

Finally, the digital twin can be used to support decision-making through various business intelligence (BI) software packages. The application of the concept of digital twins to support the production and servicing processes of technical objects has the potential to significantly improve the efficiency and effectiveness of these processes.

By providing real-time information about the performance of technical objects and potential issues, digital twins can help decision-makers make better decisions regarding the operation and maintenance of these objects. This can lead to cost reduction, improved quality, and increased productivity.

The algorithm is implemented in four steps, as depicted in the block diagram showing the interactions between each step of the algorithm.

2. Major technological challenges

The technological challenges include determining the desired error patterns that would allow to recognize the first symptoms of an impending failure or a decrease in the quality of work leading to the degradation of the device and to estimate the current state of wear.

Another technological challenge to be solved will be monitoring the right elements in terms of deviations from normal operating patterns, various measurement signals from sensors, as well as selecting from a very large amount of data that are typical of the device's operating state. It is also difficult to define the exceeding of acceptable tolerance limits, which may consequently lead to emergency states. The concept assumes the development of patterns of tested parameters in abnormal operation states (resulting from failure states). The emergency condition may be the result of failure of one or many elements at the same time (parallel failure). A failure condition leads to a departure from the standard operating pattern. Another challenge in improving operational processes and maintenance activities will be to take into account the simultaneous mapping of static and dynamic aspects for a given system. [3, 4, 6, 10]

Equally important when monitoring the operating parameters of devices will be the development of methods for capturing external disturbances that can artificially indicate abnormal operating states. Such problems may result, for example, from vibrations, network disturbances, electromagnetic radiation. The compromise between obtaining the highest quality control of machine operation and the minimum requirements for data acquisition will be important.

An important issue here is the degree of complexity of the models, because it will affect the amount of data necessary to verify the model and the amount of data to be acquired. Research will focus on appropriate models that will determine the states of a single device, and then will be implied to other technical objects.

Another issue will be the creation of a digital twin for the purpose of improving the processes of equipment operation and their maintenance system. Augmented reality technology will be useful here.

The next challenge is to develop a data transmission and acquisition system. This system is to be a "Digital Twin" ensuring accurate, digital mapping of the condition of the technical facility during its operation. The key is to map the current state by specifying the controlled parameters. At the same time, it must have the capacity to transmit and acquire all key signals. The data will be transmitted with a fixed frequency to the diagnostic center via a wireless link, which will ensure monitoring of the system and significantly accelerate its diagnostics and repair. In addition, this system will be a virtual black box - recording the time and degree of damage to the element.

The challenge is to identify various forms of damage to systems / subassemblies / components of the object that may occur during its use. The analytical activities carried out in this area are intended to determine the criticality of damage and identify the wear processes of the object's elements. It is difficult to catch the right patterns of correct work, because they are different for the work cycles of the object due to the characteristic activities, it is necessary to determine the correct work pattern separately for each of these activities. Load also has an effect.

Another challenge is to define deviations that are within the assumed tolerance. It may be necessary to lead to incorrect actions to be able to verify the operation of the algorithm model. When creating predictive algorithms, you will have to face many challenges and barriers, the most difficult tasks will be:

- analysis of available data sources that can be used for diagnostics and monitoring of installations, devices, infrastructure,
- limiting the possibility of obtaining a knowledge base based on expert opinions, which will affect the precision of defining strategy systems,
- acquisition and identification of the appropriate number of factors affecting the precise determination of the functioning of the system for recognizing characteristic patterns of impending faults.

In addition, all collected data will be subject to uncertainty:

- measurement uncertainty of devices (raw test data),
- estimated uncertainty of data defining working conditions.

3. Verification of mathematical models

Verification should take place by comparing the experimental data obtained on the basis of the signature analysis extracted from the characteristics collected from the sensors installed in the individual components of the device. Confirmation of the compliance of the digital model with the technical object will take place by using the model to recognize the approaching state of failure, which will enable conclusions on maintaining reliability. In order to catch the proper signatures characteristic for the proper operation of subassemblies, a thorough knowledge of the structure and principles of operation of a technical object is necessary. It will enable the installation of a set of sensors in adequate places from which data will be recorded online by hardware modules equipped with controllers.

An important element affecting the credibility of forecasts is the analysis of historical data on damage and failures.

In terms of developing algorithms, the following methodologies will be useful:

- dynamic programming - the problem is divided into several, the importance of each of them is assessed and the results of the analysis of some simpler problems are used to solve the main problem;
- linear programming;
- we evaluate the solution to the problem by a certain quality function and look for its minimum;
- heuristics;
- expert assessment.

4. Negative effects of the existing preventive system

In high-volume production or transportation, failures can have negative safety and financial consequences. In extreme cases, they can also be the cause of accidents in which there is loss of health and life of many people. Currently, most manufacturers and carriers base their maintenance system on preventive strategies, using primarily manual measurements and readings performed by various employees and then manually entering into documentation. This is what the army, for example, does. Throughout the entire data flow process, with the use of human factors and manual data entry into documentation, an error can occur at any stage of the flow. In some cases, there are solutions based on the implementation of predictive strategy tools, but they are limited to individual components. However, currently, due to the growing customer requirements for increased security and reliability of the services provided, such a procedure is far from sufficient. For this reason, it is expected that the solutions currently being developed will enable reliable maintenance based on intelligent systems and the combination of the concept of proactive maintenance and integrated security tools.

In the world of Industry 4.0, many industrial manufacturers have or plan to implement a digital transformation strategy that includes technologically augmented machines with wireless connectivity and sensors. The devices are connected to a system that can visualize the entire production line, control it and make decisions on its own. This digital transformation describes the trend towards automation and data exchange in manufacturing technologies and processes. Thanks to this, it will be possible to solve the currently critical problems in transport systems and large-series production, such as transport safety, disruptions and delays as a result of eliminating the effects of failures, deviations from the originally planned schedule due to the need to modify the plan. [8, 9, 10]

Currently, most maintenance managers apply preventive maintenance strategies, which are based primarily on systematic service and planning periodic inspections and repairs resulting from technical documentation. It is assumed that the inspection intervals are set in a correct and optimal way (taking into account profitability). Meanwhile, there is a wide range of available sensors on the market that facilitate the collection of huge amounts of data on the parameters and operational characteristics of devices. However, it is essential that this data is subject to integrated analysis in real time, as this allows future problems to be detected before they actually occur. An important innovation is therefore an integrated approach to the collected diagnostic data, which takes into account signals from many components of the facility, allowing to assess the technical condition in real time. This is possible thanks to the implementation of comprehensive predictive solutions that guarantee continuous monitoring of equipment elements of the device by measuring all relevant variables, such as temperature, vibration (vibration), operation of components, etc.

The diagnostics carried out are primarily used to collect operating data, which are the basis for determining the optimal times for maintenance, replacement or repair work. Measurement data from sensors monitoring the condition of the facility are continuously analyzed by a diagnostic algorithm that sends feedback in real time about the possible risk of failure. Thanks to this, the created big data sets supply the system of proactive identification and elimination of faults, which reports the necessary maintenance interventions. The developed damage analysis based on the virtual reality subsystem shows the service technician the elements that should be the subject of maintenance operations, but also the scope of necessary actions.

5. Construction of a digital twin for the purpose of improving the operation processes of technical facilities and their maintenance system

The concept of a digital twin assumes the coexistence of three elements:

a) a physical object in real space;

b) a virtual object;

(c) a data and information link system that connects virtual and real products.

What is important in the created solution for the improvement of operational processes and maintenance activities is the possibility of simultaneous mapping of static and dynamic aspects for a given system. "Digital twins" are one of the tools supporting the concept of Industry 4.0, but their implementation dominates primarily in the strategies for maintaining production machine parks. However, a solution to this concept is also possible in the area of transport management. Thanks to the "digital twin", it will be possible to map the real behavior of individual subassemblies and elements and to study how the process of use and current operating conditions affect the state of fitness. The twin can also be used to conduct virtual experiments regarding changes in the operation and maintenance process. It provides the opportunity to find a solution to a problem by improving the product or changing operating procedures before a catastrophic failure occurs. A digital twin for an integrated system that monitors the status of individual subsystems that are subject to diagnostic assessment in real time. The possibility of mapping the actual behavior of individual components in specific operating conditions. Evaluation of the impact of the use process and the impact of current operating conditions on the performance of the device. Possibility of solving existing problems in the exploitation process through the implementation of virtual experiments with the participation of a digital twin. Evaluation of the impact of changes in maintenance procedures and changes in the operation process based on virtual experiments.

6. On-board diagnostic system

The basic element on which the concept of digital twins will be based is the construction of a model of the on-board diagnostic system. In this, signals with different characteristics (digital, analog, fast and slow) are to be recorded. The selection of individual measurement paths will be carried out based on:

- analysis and identification of the wear processes of the object's elements, which are important in terms of reliability,
- linking specific wear processes with measurable physical quantities (temperature, vibrations, etc.)
- development of predictive models for selected forms of damage,
- design and implementation of a monitoring system for predetermined physical parameters (construction, assembly, technical and operational guidelines will be developed),

- performing tests of the model in conditions similar to the pilot ones for the purpose of identifying the values of parameters/signals and disturbances generated by the object and the environment, including testing components in various states of degradation.

In this approach, it is important to define the initial calculations on the real object, the size of the transmitted data as well as the scope of calculations and the form of calculations outside the object, which will include: construction of the monitoring and information flow system, method of acquisition and transfer of measurement data to the processing center, method of analyzing the recorded measurements, and error handling, development of communication procedures. The specified method of data registration and transmission should take into account the minimization of transmission costs and minimization of transmission errors while maintaining the correctness of data and the amount necessary for proper inference. The selection of sampling on the sensors, the method of data collection and the frequency of data transfer to the central system should be carried out. Expert knowledge can be used to identify and quantify failure causes and effects. Based on the assessment of damage effects (or an identified sequence of interdependent damages), damages can be assigned to the following groups:

a) safety-critical damage,

b) environmental critical damage,

c) failures that have a critical impact on the performance of functions;

d) other.

The conducted classification will allow to assess the completeness of the collected signals about wear processes. An important issue here is the use of operational data needed in the next steps to build models of the correct behavior of equipment elements and to define features that support the automation of detecting emergency situations and determining the current condition.

7. Conclusions

The proposed concept should contribute to many benefits from the operation of the devices:

- it will allow proactive diagnosis of the condition of technical objects in real time and report actions to ensure the continuity of traffic;

- support technical services with a predictive failure prevention (PdM) strategy, through online monitoring of parameters determining the current state of controlled installations,
- it will facilitate the operation of technical services and shorten repair times by providing them with automatic, ready-made recipes for solving the problem;
- it will accelerate and simplify the implementation of the strategy of maintaining modified and modernizing facilities on the basis of the knowledge base about the system;
- will provide an effective tool in the event that automatic generation of information on technical condition is required;
- will support decision-making processes;
- the "digital twin" will allow for the improvement of exploitation processes and their maintenance system.

There is a need for further research, particularly focusing on the development of new algorithms, construction of new models, their examination, and the implementation of neural networks.

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