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DIGITAL TWIN DATA STORAGE FOR INDUSTRIAL ROBOT KINEMATICS

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In response to the increasing demand for efficient and automated production processes, Digital Twins have emerged as a vital tool for optimising industrial operations and preemptively identifying equipment issues. An important component of the Digital Twin is the storage of historical data on equipment operation. This research focuses on developing a universal database structure for storing position data of various industrial robots, including Cylindrical, SCARA, Articulated, and Cartesian/Gantry robots. The proposed database uses the Denavit-Hartenberg (DH) method, widely recognised for representing robot kinematics. Combining the Denavit-Hartenberg method with relational database technology provides a flexible and scalable solution for managing the diverse and complex data associated with robot configurations. This structure makes it possible to apply this development in industrial environments where robots with different degrees of freedom and different kinematic chains are used. The combination of the Denavit-Hartenberg method with relational database technology provides a flexible and scalable solution for managing diverse and complex data related to robot configurations. The database design supports the creation of Digital Twins for industrial robots, facilitating enhanced operational monitoring, predicting maintenance, identifying wear patterns, detecting abnormal behaviour and predicting potential equipment failures. This approach minimises downtime and extends the lifetime of robotic systems, which ultimately contributes to sustainable production and is in line with the concept of Industry 4.0. In this study, we present a database framework specifically for storing data on the position of equipment nodes. The created entities allow storing data on the position of each robot node. When the position of a node changes, only those Denavit- Hartenberg parameters that have changed are stored in the database. This allows you to optimise memory usage without losing the collected data. The database structure can be expanded by adding data from other sensors installed on the robot or other peripheral devices, or data generated by the Digital Twin. Further research will test the effectiveness of the database structure.

Key words: *Digital Twin, Data Storage, Industrial Robotics, Kinematics, Denavit-Hartenberg Method.*

Палажченко Є. В., Шендрик В. В. Сховище даних Цифрових Двійників для кінематики промислових роботів

У відповідь на зростаючий попит на ефективні та автоматизовані виробничі процеси, Цифрові Двійники стали надзвичайно важливим інструментом для оптимізації промислових операцій та завчасного виявлення проблем з обладнанням. Важливим компонентом Цифрового Двійника є сховище історичних даних про роботу обладнання. Адже зібрані дані можуть бути використані для аналізу, моделювання та оптимізації. Це дослідження зосереджене на розробці універсальної структури бази даних для зберігання даних про положення різних промислових роботів, включаючи циліндричних, SCARA, шарнірних та декартових/портальних роботів. Запропонована база даних використовує метод Денавіта-Гартенберга, який використовується для представлення кінематики роботів. Така структура дозволяє застосовувати цю розробку в промислових умовах, де *використовуються роботи з різним ступенем свободи і різними кінематичними ланцюгами. Поєднання методу Денавіта-Гартенберга з технологією реляційних баз даних забезпечує гнучке і масштабоване рішення для управління різноманітними і складними даними, пов'язаними з конфігураціями роботів. Дизайн бази даних підтримує створення Цифрових Двійників для промислових роботів, що полегшує оперативний моніторинг, прогнозування технічного обслуговування, визначення моделей зносу, виявлення ненормальної поведінки та прогнозування потенційних відмов обладнання. Такий підхід мінімізує час простою та подовжує термін експлуатації роботизованих систем, що в кінцевому підсумку сприяє сталому виробництву та відповідає концепції Індустрії 4.0. В цьому дослідженні представлено каркас бази даних саме для зберігання даних про положення вузлів обладнання. Створені сутності дозволяють зберігати дані про положення кожного вузла робота. При зміні положення вузла в базі даних зберігаються тільки ті параметри Денавіта-Гартенберга, які змінились. Це дозволяє оптимізувати використання пам'яті не втрачаючи при цьому зібрані дані. Структура бази даних може бути розширена додаванням даних з датчиків встановлених на роботі, периферійних пристроїв, або ж даних згенерованих Цифровим Двійником. В подальших дослідженнях буде перевірено ефективність використання структури бази даних.*

Ключові слова: *Цифровий Двійник, база даних, робототехніка, кінематика, метод Денавіта-Хартенберга.*

Introduction. Modern production trends and the level of automation development motivate companies to create Digital Twins of equipment and processes. Digital Twin technology optimises production processes and helps to identify equipment problems in advance. It makes the entire production process cheaper by simplifying equipment development, operation, and maintenance. Digital Twin optimises processes and speeds up production readjustment. The growing interest in this topic among scientists and companies' application of this technology creates an excellent potential for future development.

Digital Twins are used in urbanisation, manufacturing, medicine, robotics, agriculture, military/aviation, and mobile networking/communication [1]. Robotics and manufacturing are two areas where Digital Twins are actively used. Digital Twins are applicable for individual instances of equipment [2] and entire virtual factories [3]. Various industrial robot manipulators are used depending on the needs and purpose. Cylindrical, SCARA, Articulated, Cartesian/Gantry and Delta/Parallel robots are the most common in the industry [4]. Different robots are used in various spheres of life, such as industry, laboratory research, food industry [5], medical field [6], and additive manufacturing [7], and scientific research [8].

After all, they can perform different functions and come in various sizes. The variety of types of robots makes it a difficult task to create a universal database for storing data about their position. After all, all these types of robotss have different kinds of connections. So, depending on the type and purpose of the Digital Twin, the structure for storing data can differ.

This paper focuses on creating a universal database for storing position data for Cylindrical, SCARA, Articulated, and Cartesian/Gantry robots.

The project's relevance is due to the need to create a universal database for storing the industrial robots' position data. This development will significantly facilitate the initial stages of work on creating a Digital.

The objectives of this study include a thorough analysis of the various methods used to represent the kinematics of industrial robots. It also involves evaluating the existing technologies for database creation within the fields of robotics and industry. Additionally, the study aims to develop a robust database structure specifically designed for storing robot data.

Literature analysis. A Digital Twin has a complex structure. It is not just a digital model Figure 1. The concept of a Digital Twin includes a wide range of technologies. For a Digital Twin to function correctly, it needs a Communication System to exchange data between the physical and digital worlds. The Physical Twin must be equipped with appropriate sensors to collect information. Simulation tools for predicting the behaviour of the physical counterpart and tools for analysing the functioning and state of the system are also crucial for a Digital Twin. A user interface for interacting with the equipment is also part of a Digital Twin model. A database in this scheme is a component for accumulating archive data on system operations. This data can be used to analyse equipment changes and the preconditions for anomalous behaviour or errors.

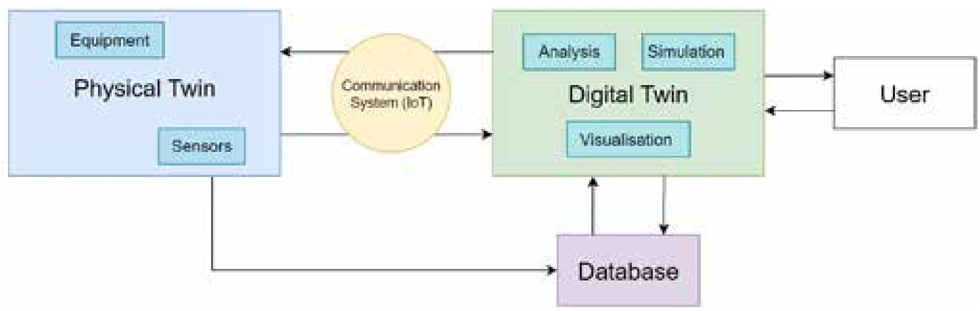

Fig. 1. Digital Twin structural model

To accurately describe a robot’s current position, it is insufficient to know only the coordinates of the final joint. To fully describe the robot’s state, it is necessary to consider all connections’ positions. The more degrees of freedom a robot has, the more flexible and functional it can be in performing various tasks. Degrees of freedom determine the number of independent movements a robot can make. However, increasing the degrees of freedom also increases the combination of possible joint positions for the same endpoint position.

The Denavit-Hartenberg method is a standard method for displaying the position of robot joints. It uses four parameters: a-link length, α(alpha)-link twist, d-link offset, and θ(theta)-joint angle. The initial values of these parameters describe the relationships between the moving elements of the robot. Some of these parameters may change during movement depending on the joint type. Using this method, we can describe the state of the joints for different types of robots. Moreover, this method can be applied to robots with different degrees of freedom. This method has been used for the 4-degrees of freedom SCARA robot [9], Cylindrical robot [10], Kuka robot [11], and Gantry robot [12].

In addition to using the classic Denavit-Hartenberg method, there are other ways to calculate kinematics. The Modified Denavit-Hartenberg method is a variation of the original convention. It alters how some parameters are assigned to improve accuracy, for example, when calibrating a robot. [13]

The Product of Exponentials (PoE) Method is also often used in robotics to describe the forward kinematics of a robot using a sequence of exponential maps. They can be converted to the DH method and vice versa if necessary. For example, the robot can be calibrated using the PoE method and DH parameters. [14]

Screw theory is a mathematical framework that represents motion and force in terms of screws, which are six-dimensional vectors combining linear and angular components. [15]

Hyper-Dual Quaternions combine body pose (translation and rotation) and body velocities into a compact representation, eliminating the need for additional pose differentiation. [16]

Lie Algebra and Lie Groups, Homogeneous Transformation Matrices, and other methods are also used to describe forward and reverse kinematics. While each method is employed to describe kinematics, they each have advantages and disadvantages. The appropriate method is selected based on the specific task requirements.

Each robot has its technical characteristics given by the specification: weight, Work Envelopes, speed and acceleration characteristics, and the permissible error value. Also, the robot's functionality depends on the equipment installed on it. It can be an extruder, gripper, screwdriver, drill or other tools. It is challenging to universalise information about the operation of these tools because they can differ significantly in their functionality. These parameters are essential for creating a Digital Twin because only the totality of all parameters can fully characterise the system's state. Depending on the purpose and tasks, the robot can perform different actions. They may be repetitive or depend on the changing environment. In any case, to track wear, abnormal behaviour and equipment errors, it is necessary to compare the actual position with the predicted position of the robot.

Based on the comprehensive systematic review and bibliometric analysis [17], most Industry 4.0 solutions are developed within the Digital Shadow and Digital Twin. These solutions are underlying assumptions that humans are the primary end-users of the information. Integration emerges as the dominant data management challenge because the data management component performs a bridging function. Additionally, cloud computing and storage are identified as the principal technologies employed in implementing Data Management solutions.

The literature reports [18] a series of system architecture proposals for Intelligent Manufacturing Systems, which are primarily data-driven. Many of these proposals treat data storage solutions as entities supporting the architecture's functionalities. However, choosing which logical data model to use can significantly affect a system's performance. The suitability of relational and NoSQL databases for different scenarios within Industry 4.0 depends on the data's volume, variety, velocity, veracity, and value.

SQL databases are highly effective at managing structured data, making them ideal for scenarios where the data generated by Digital Twins is consistent and well-defined. At the same time, NoSQL databases can handle various unstructured data from multiple sources.

Cloud-based services [19] are also used to build the Digital Twin data management architecture. Typically, such services are used for complex systems that collect and analyse information from several types of Digital Twins. In this case, there is a need for large capacities to process a massive amount of information.

One of the tasks of Data Management is to create an architecture for data storage. Cloud services can process and store large amounts of data. However, it is also possible to create an on-premises architecture. The choice of technologies and tools depends on the tasks, data type, and volume.

Database Development. The Denavit-Hartenberg model has gained wide acceptance in society. Many algorithms have been formulated using this model, and numerous commercial industrial robots are programmed with it. If we use the Denavit-Hartenberg method, a position data of a robot has a predetermined structure regardless of the type of connections. Therefore, relational databases are well suited for this task. By combining the Denavit-Hartenberg method and relational databases, we get a simple structure that can store robot position data for different types of robots.

For this purpose, we defined six tables that can store the necessary entities.

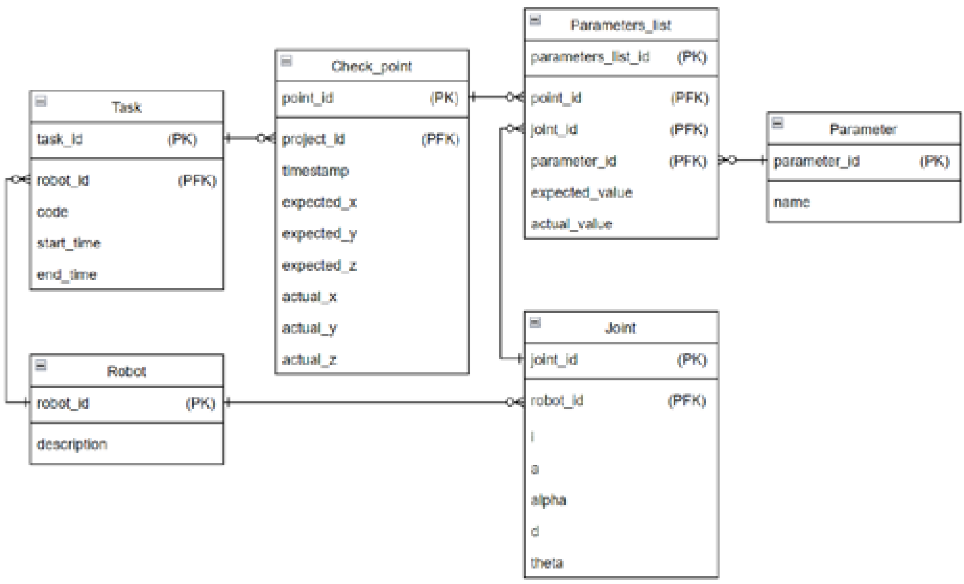

Fig. 2. Entity-Relationship diagram

The central entity is a Robot. A robot can have several joints, the relationships and positions of which are described using Denavit-Hartenberg parameters. Each robot has a task to perform. A checkpoint is used to control the robot's position during the execution of a task. This entity contains the expected and actual coordinates. A Digital Twin simulation tool can generate expected coordinates, and actual coordinates are obtained from a Physical Twin. The "Parameter" entity contains only a unique identifier and the name of one of the four parameters: a, α(alpha), d, and θ(theta). The "Parameters_list" entity stores the connection parameters. While the robot is moving, some parameters remain unchanged, depending on the type of connection. Therefore, a flexible structure was developed for the economical storage of parameters. The "Parameters_list" contains the checkpoint identifier, joint identifier and parameter identifier, the expected and the actual parameter value. This structure allows to store only the variable parameters for each joint.

This database schema is only the basis for storing the exact position of all robot nodes. This database model can be expanded and adapted depending on the needs. For example, tables can be added if additional data from sensors and other components must be stored. This approach can work for different types of robots. The Denavit-Hartenberg method is quite flexible in combining different types of joints in one mechanism.

Table 1

Description of database fields

Table	Name	Type	Description	Key	Restrictions
Robot	robot_id	Int	Unique identifier for robot	Primary Key	Not Null, Unique
	description	Text	A description of the robot		
Joint	joint_id	Int	Unique identifier for joint	Primary Key	Not Null, Unique
	robot_id	Int	References the robot		
	i	Double	The sequence number of the connection		
	a	Double	DH parameter 'a'		
	alpha	Double	DH parameter 'alpha'		
	d	Double	DH parameter 'd'		
	theta	Double	DH parameter 'theta'		
Task	task_id	Int	Unique identifier for a task	Primary Key	Not Null, Unique
	robot_id	Int	References the robot		
	code	Text	Set of commands to perform		
	start_time	Datetime	The start time of the task		
	end_time	Datetime	The end time of the task		
Check_point	point_id	Int	Unique identifier for checkpoint	Primary Key	Not Null, Unique
	task_id	Int	References the task		
	timestamp	Datetime	The timestamp when the checkpoint was recorded		
	expected_x	Double	Expected X coordinate		
	expected_y	Double	Expected Y coordinate		
	expected_z	Double	Expected Z coordinate		
	actual_x	Double	Actual X coordinate		
	actual_y	Double	Actual Y coordinate		
	actual_z	Double	Actual Z coordinate		
Parameter	parameter_id	Int	Unique identifier for the parameter	Primary Key	Not Null, Unique
	name	Varchar	The name of the parameter		
Parameters_list	Parameters_list_id	Int	Unique identifier for parameters list	Primary Key	Not Null, Unique
	point_id	Int	References the checkpoint		
	joint_id	Int	References the joint		
	parameter_id	Int	References the parameter		
	expected_value	Double	Expected value of the parameter		
	actual_value	Double	Actual value of the parameter		

Conclusion. This research presents a comprehensive solution for managing the position data of industrial robots through a universal database structure based on the Denavit-Hartenberg method. The proposed database effectively handles the complexities associated with different types of robot kinematics, making it a versatile tool for creating Digital Twins. The structure's adaptability ensures that it can accommodate additional data types and sensors as needed, providing a scalable platform for future developments in robotics and automation. This work contributes to the broader field of Industry 4.0 by addressing critical challenges in data management and integration, thereby enhancing the efficiency and reliability of digital manufacturing systems.

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