DESIGN AND DEVELOPMENT OF DIGITAL TWINS IN SIMULINK

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Abstract:

A digital twin is a real-time, dynamic digital representation of a physical system, enabling continuous monitoring, simulation, and analysis. It plays a crucial role in optimizing system performance, predictive maintenance, and decision-making across various engineering domains. Simulink, a MATLAB-based software environment, is widely utilized for modelling and simulating complex dynamical systems through block diagrams.

This paper aims to explore the development process of digital twins within Simulink, highlighting its capabilities for system-level design and validation. Simulink provides engineers and researchers with powerful tools to create, simulate, and optimize digital twins of physical systems. By integrating real-time data, these models enable accurate performance evaluation, fault detection, and predictive analytics, making them essential for industries such as aerospace, automotive, robotics, civil engineering, and manufacturing.

The study outlines key methodologies for developing digital twins in Simulink, emphasizing their role in enhancing system reliability, improving operational efficiency, and accelerating innovation. Additionally, it discusses Simulink’s features, such as its multi-domain modelling capabilities, simulation accuracy in real time, and integration with real-world data sources, which contribute to the improvement of digital twin technology. It is demonstrated that Simulink-based digital twins facilitate engineering decision-making, streamline system optimization, and drive technological advancements in industrial applications.

Keywords:

Digital Twins, Design and Development, Modelling and Simulation, Optimization, Simulink.

INTRODUCTION

A digital twin is a virtual representation of an entity (e.g. object, process, system, machine, or device) designed to reflect physical properties and behaviours accurately. It is updated from real-time data and uses simulation, machine learning (ML) and automated reasoning to help make decisions. A digital twin is a virtual replica that allows for real-time monitoring, simulation and analysis. The digital twin enables performance optimization, better decision-making, faster problem solving and more efficient management of resources. The properties of the digital twin are crucial for its successful use in various industries, such as aerospace, automotive, civil engineering, maintenance, education, manufacturing, robotics, for system-level design. [1]

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A digital twin is a virtual replica of a product, process, or system—whether in operation or under development. For assets in operation, the digital twin reflects the current condition and incorporates pertinent historical data. Digital twins are used for evaluating an asset's current state and to predict future behaviour, refine control systems, and optimize the operation of systems, either objects or processes. In the development procedure, the digital twin acts as a model of a product to be built, process, or system that facilitates development, testing and validation. [2]

MATLAB [3] and its Simulink [4] toolbox (both products of MathWorks, USA) offer platforms for the creation, simulation, verification and ultimately implementation of specific digital twins. Simulink offers a set of tools and features to create, simulate, and optimize digital twins of real systems. The combined physics-based modelling, advanced data analytics and Artificial Intelligence (AI) tools, and options for easy deployment (Programmable Logic Controllers - PLCs, embedded systems, web, cloud), enable engineers and designers to obtain directed design of digital twins that enhance the understanding, operation and maintenance of complex entities. [2]

Digital twin platforms are changing various commerce sectors with powerful capabilities that facilitate data-driven choices, predictive maintenance, and real-time monitoring. These platforms provide unique perspectives that drive efficiency, creativity, and environmental awareness in industries, including manufacturing, healthcare, energy, transportation, construction, and the economy in general. [5]

Digital Twins can also be perceived as models of real or virtual entities (objects, components, systems or processes) which extend options for operation simulation and evaluation of different scenarios.

2. MODELLING AND SIMULATION

Modelling and simulation are well-established and often exploited in engineering for design and automation of processes [6]. System or model identification and automatic control are valuable in contemporary engineering and industrial automation. Simulink [4] is a specialized software that enables efficient modelling of the design, operation simulation and analysis of complex systems. In the following part, the key aspects of how to use Simulink for automated modelling are discussed briefly. Also, the key components of MATLAB and Simulink which are exploited in modelling and simulation of automated systems are concisely explored.

Simulink is a software environment for modelling, simulation and analysis of a multi-domain dynamical systems described by block diagrams. Simulink uses a graphical description (by Simulink Blocks) to visually represent system components and their interactions. For example, modelling a production conveyor belt uses blocks for its conveyor, robotic arms and controls to compose a description and model the entire system. Simulink is user friendly since block diagrams of systems can be made by drag-and-drop of standard modules and components selected from a menu.

For control logics, the state flow diagrams are used to define and model complex decision-making processes and behaviour, depending on the overall state in automated systems. This determines the control logic in the existing system. For example, in an automated traffic light system, timely state transitions and vehicle detection in real time can be designed, clearly defining the engineering logic for each state (or colour) of the light.

Specific tools and features in Simulink help engineers to create, implement and exploit Digital Twins. The development of a digital twin in Simulink has the ability to significantly improve the simulated processes and analysis of physical systems. The benefits of using digital twins in Simulink are the following: improved efficiency, reduced costs and enhanced innovation. The key features of Digital Twin models in Simulink are expressed as real-time data visualization and predictive maintenance. Both digital twins and Simulink are applied in various industries.

Simulink offers an appropriate set of tools and features to create, simulate, optimize Digital Twins of real systems. Simulink provides several utilities which are aimed to create precise and efficient digital twin models that can be used for various applications, such as predictive maintenance, performance optimization and simulation of different scenarios. These tools and toolboxes allow for real-time simulation, predictive maintenance, optimization and visualization of system behaviour. Options provided by Simulink are:

1. Simulink 3D Animation: Visualize and simulate digital twin in 3D, providing an intuitive representation of the system's behaviour;
2. Simulink Real-Time: Simulink Real-Time is used to run real-time models for hardware-in-the-loop (HIL) testing. This module allows one to run the model on hardware in real-time and interface it with real-world data. It is important for hardware-in-the-loop (HIL) simulation, where the test model (or system emulation) is implemented

in a real-world environment. This is essential for automating processes in aerospace or automotive applications, such as assessing the accuracy of control algorithms in real time while interacting with real, existing, operating hardware;

3. Stateflow [7]: Stateflow is a product of MathWorks that provides a graphical language which includes state transition diagrams, flow charts, state transition tables, and truth tables. Stateflow fosters modelling of complex logic and behaviour in the digital twin, such as state machines, events and transitions occurring in the physical system;
4. MATLAB Integration: MATLAB is used in parallel to Simulink for data analysis, visualization and more sophisticated algorithms that may not be directly implemented within Simulink. Integration with MATLAB provides additional sensor data analysis and system behaviour optimization;
5. Simscape [8]: The Simscape enables developers and designers to rapidly create models of physical systems within the Simulink environment. This module extends Simulink to simulate physical systems, including mechanical, hydraulic, and electrical components, or thermal systems. For example, modelling a robotic arm in the Simscape, which requires precise control of joints and movements of segments provides a simulation of relevant physical interactions, making it easier to optimize overall performance. Simscape module is suited for simulating the behaviour of components and entities that formed a digital twin.

The MATLAB modules that complement the use of Simulink in creating digital twins are Statistics and Machine Learning Toolbox and Deep Learning Toolbox.

Additional resources provided by MATLAB and Simulink modules that can help in the design and development of a digital twin are Signal Processing Toolbox and Control System Toolbox.

Simulink's Control System Toolbox offers predefined PID controllers (having Proportional, Integral and/ or Derivative action - PID) for automating specific processes. PIDs have editable parameters providing ease-of-use in implementation.

Simulink's Signal processing tool is used for filtering and processing signals in automated systems. In an automated quality control system, data acquisition and processing can be modelled to detect defects in products using available image processing techniques.

All these modules and toolboxes create a powerful set of tools for developing digital twins that are to be used in various industries and applications e.g. to predict the performance of a drilling rig in real time, [9].

Automation of management strategies is realized by building adaptable management systems, which responds and adapts to data in real time. For example, in a smart HVAC (Heating, Ventilation and Air-conditioning) system, control logic can be adjusted based on room occupancy and weather conditions to optimize energy consumption.

Simulink software allows running simulations under different conditions to evaluate the performance of selected systems. In an automated warehouse, different scenarios of inventory levels and order fulfilment rates can be simulated, in order to evaluate the performance of the logistics management system.

MATLAB scripts can be implemented to automate tasks in Simulink. For example, scripts can be created that automatically adjust model parameters based on optimization results, governing/ driving/ directing the model tuning process for an automated process control system. Simulink options are used to generate automated reports from simulations, summarizing performance metrics, model parameters, and results. This can be particularly useful in projects where compliance of documentation (with standards), or analysis, is required.

3. DESIGN OF DIGITAL TWINS

The development and design of a digital twin represent a dynamic and innovative approach to the simulation and optimization of physical objects and systems. A digital twin replicates a physical entity or system, enabling real-time data analysis. [10]

Despite the variety of digital twin use cases, there are similar strategies to make successful implementation of digital twins. These strategies are usually the following: define clear objectives and scope, design and build, perform testing and validate, deploy and operate, monitor and update. [2]

These strategies are sometimes called the digital twin product development stages, e.g. in [5] or the key steps in the development of a digital twin as in [11]: defining goals, collecting data, creating models, integration with IoT (Internet of Things), analysis and simulation, optimization and improvement.

The first step in the development of a digital twin is to clearly define the goals and purpose of a digital twin which is being built. Then it is necessary to collect all relevant data from various sources, including sensors, IoT devices and historical data [12].

Based on the collected data, a virtual model is then created. Specialized software such as CAD (Computer-Aided Design) and simulation tools are used to create 3D models. For example, Autodesk Fusion 360 can help develop a model – a 3D visualization of a physical system and ultimately design and build its digital twin or the real object.

The digital twin connects to IoT platforms in order to receive data in real time. For example, for connecting physical objects with digital models platforms such as Microsoft Azure IoT, or AWS IoT can be used.

After integration, analyses can be carried out based on simulations. These can include predictive maintenance, when data is analysed to predict failures before they occur. Based on detailed analyses, the digital twin can help significantly improve, enhance, and optimize the overall performance of the system under consideration.

Validation and verification are critical steps in ensuring the digital twin potential to accurately reflect a physical counterpart and its expected performance. By using the high-integrity verification workflow, engineers use simulation-based testing and static analysis to detect some defects, damages and to shorten the time to the final market. Moreover, the priority is to adhere to standards and maintain high product quality.

The stages of digital twin product development are presented in Figure 1. [5]

The more detailed steps to design effective digital twin solution for manufacturing are given in Figure 2. [11]

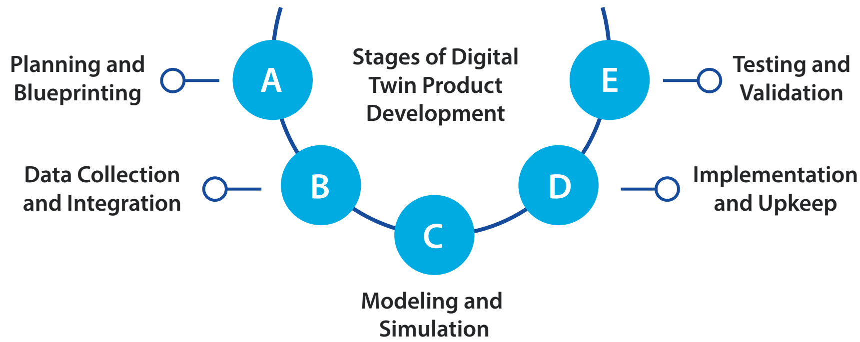

Figure 1. Digital Twin Product Development Stages or Phases[1]

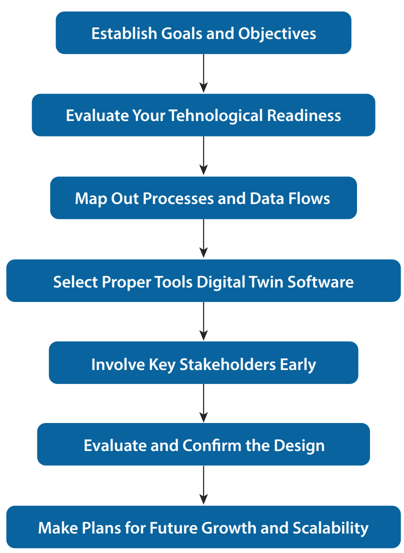

Figure 2. Steps to Design an Effective Digital Twins Solution for Manufacturing[2]

1 Source: https://a.storyblok.com/f/122804/1600x1000/2c4914f8fa/stages-of-digital-twin-product-development.webp
2 Source: https://a.storyblok.com/f/122804/3201x3868/a3467ad142/steps-to-design-effective-digital-twin-solutions-for-manufacturing.webp

Development of a digital twin is a process which usually lasts several weeks to months, depending on its complexity and use intended [5].

Digital twins for Cyber-Physical Systems (CPSs) have been built using different methods, e.g. application of model-based systems engineering approach and ML techniques. The CPS model refers to a virtual replica or representation of the CPS, which simulates the CPS behaviour. [13]

The digital twin of CPS consists of two main components:

1. Digital twin model; and
2. Digital twin capability.

The elements of digital twin and their interactions are displayed in Figure 3. [13]

Digital twins created in Simulink can be exploited to enhance the design, monitoring, and maintenance of complex technological systems. By leveraging real-time data and advanced simulation capabilities, engineers can acquire deeper insights that drive operational efficiency, enhancements and innovation in many areas.

4. THE PERFORMANCES OF DIGITAL TWINS

The performance of the digital twin is crucial for its successful exploitation in various use cases and industries. Here are briefly described some aspects of the digital twins' implementation and optimisation achieved by these.

I. Real-time Data Processing: The rate and efficiency of processing the data collected from the sensors significantly affect the performance of the digital twin. The latency of the system will be reduced using edge computing technologies since data processing is then performed closer to the data source;

II. Data Quality: The accuracy and relevance of the data used by the digital twin is important for its performance. Implementing a system for collecting, testing, validating and cleaning data can help to ensure its high quality;

III. Model Complexity: More complex models provide more detailed analysis, albeit digital twins' operation could be made slower. Developing simplified models for quicker analysis and more complex models for more accurate and detailed analysis can improve overall performance;

IV. Interoperability: The capability of the digital twin created to communicate with different systems and platforms can affect its effectiveness. Using standardized protocols and APIs (Application Programming Interfaces) makes it possible to improve interoperability;

V. Simulation and Prediction: The accuracy of simulations and predictions directly affects the implementation and applications of the digital twin. Applying ML models that are trained on historical data can improve predictive capabilities and prediction accuracy;

VI. Data visualization: Data collected can be used to support relevant automated decision-making. The interactive graphs and visualizations have the ability to improve the information extraction from data;

VII. Scalability: The digital twin is adapted to scale (or increase) in size and time with respect to specified demands. Using cloud computing resources enables easy scaling in accordance with the requirements and needs.

By connecting digital twins of the machines or assets during operation with relevant data, algorithms and models, it is possible to make better decisions, improve processes and reduce the overall losses and total cost. Some research papers indicate that investment in custom digital twin development can reduce operating costs by up to 30% and boost productivity by 20% [5].

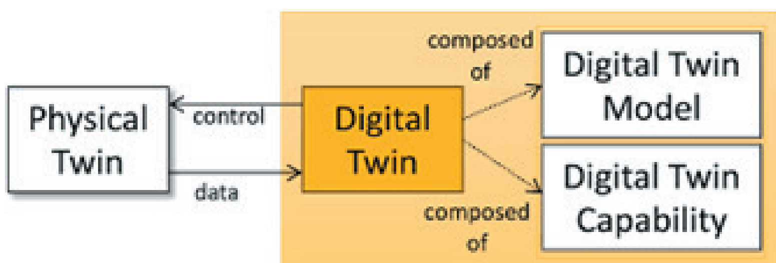

Figure 3. Digital Twin for Cyber-Physical Systems[3]

3 Source: https://arxiv.org/html/2407.18779v1/extracted/5757201/images/OverviewDT.png

5. CONCLUSION

A digital twin operates by digitally replicating a physical asset in a virtual environment, accurately mirroring its functionality, features, and behaviour. Digital twins represent a powerful tool for advancing innovation and optimizing performance across various industries. By linking the physical and digital realms, these models provide enhanced insight into system performance, enable the anticipation of potential issues, and support informed decision-making. Moreover, the integration of artificial intelligence, machine learning, and data analysis facilitates the creation of specific digital simulation models, offering a novel approach to product lifecycle management.

Simulink is a versatile and comprehensive platform that comprises specialized toolboxes and modules for modelling, simulation, and analysis of dynamic systems. It is extensively used in the development of digital twins, allowing for the creation and testing of models with high precision. By employing various simulation blocks and incorporating real-world or real-time data, robust models can be established to optimize performance and predict potential problems. This methodology is widely applied in predictive maintenance, fault detection, and overall system optimization in industries such as manufacturing, automotive, aerospace, and energy.

The development of digital twins in Simulink encompasses modelling, data integration, simulation, analysis, validation, and optimization. This process provides deeper insights into the operation of physical systems and facilitates continuous performance improvement. Several tools exist in Simulink that enable designers or developers to model complex systems specific for selected industries, to test them virtually, predict their behaviour and optimize operations, while exploiting real-time data for permanent system improvement and minimization of cost.

The objective of this work was to present a concise overview of the Simulink modules and tools used for digital twin development and implementation. Ultimately, this approach contributes to enhanced operational efficiency, cost reduction, and system resilience, driving continuous technological advancement in engineering applications.

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