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DIGITAL TWINS AND THEIR APPLICATIONS IN SURGICAL ROBOTICS

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Abstract: *Robotics is an interdisciplinary scientific field that integrates mechanics, electronics, sensing technologies, control systems, biomedical engineering, and software solutions. Due to its significant advantages, robotics has found extensive applications in medicine, particularly in surgical practice. Digital Twins are virtual, dynamic representations of real physical objects or processes that are continuously updated using real-time data or simulation-based parameters. This paper investigates the role of digital twins in engineering, robotics, and surgical robotics. A digital twin-based architecture for a surgical system is proposed. Furthermore, simulation scenarios based on digital twins for surgical robotics are analyzed. A Use Case Diagram of digital twin-assisted surgical interaction is also presented, illustrating the relationship between the surgeon, the digital twin modeling module, and patient-related surgical actions. The main objective of this study is to demonstrate the application of digital twins in surgical robotics for enhancing simulation realism, enabling the development of personalized training protocols, and improving the efficiency of healthcare delivery through virtual testing of surgical scenarios prior to real clinical procedures, ultimately leading to improved patient outcomes.*

Key words: *Digital Twins, Robotics, Surgical robots, Training, Simulating, Real-Time Data, Virtual Models.*

1. INTRODUCTION

Digital Twins are virtual, dynamic models of real physical objects and processes that are updated through real-time data or through simulation parameters [1]. Recent definitions extend the concept of digital twins beyond representation, emphasizing their capability to detect, predict, and optimize system behavior through real-time analytics [2].

Digital Twins create an interactive environment where "what if" simulations are performed, innovations are tested without real risks, enable the prediction of problems, and create conditions for automating processes.

Compared to conventional simulations, digital twins provide a continuous, two-way flow of information between the real and virtual worlds. This allows the state of the digital twin to be updated with changing real conditions and to apply intelligent feedback.

The concept is expressed in process optimization, cost reduction, increased efficiency and productivity, rapid and personalized innovations, flexibility, and strategic decision-making in a wide range of activities.

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1.1. Digital Twins in Engineering

In engineering, digital twins are used as a tool for Industry 4.0, intelligent systems, and automation. Main applications of Digital Twins include Intelligent maintenance (Predictive Maintenance), Detection of wear and damage before they occur; Reduction of downtime and costs; Optimization of processes and energy efficiency – optimal management of machines, production lines and energy systems; Simulations and "what-if" analyses – safe testing of changes in settings, loads, operating mode. They also take their place in the management of complex dynamic systems such as transport systems, buildings, industrial installations, "smart city" solutions. From their applicability arise the advantages of Digital Twins, which include higher reliability, lower costs, faster decision-making, better safety and control [3].

1.2. Digital Twins in Robotics

A Digital Twin in robotics is a virtual model of a physical robotic system, which is updated in real time using sensor data and is used for analysis, control, and optimization [4].

Main components of robotic systems based on a digital twin:

- Physical robot (Physical Layer);
- An industrial or mobile robot with built-in sensors for position, force, and monitoring;
- Sensor layer (Data Acquisition);
- Collects data in real time (IoT, embedded systems);
- Communication layer;

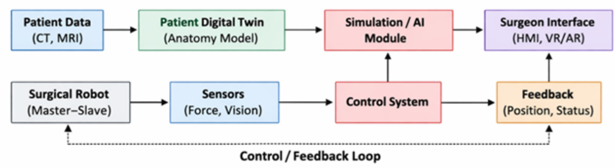

Fig. 1. Digital Twin in Surgical Robotics.

- Protocols such as MQTT, ROS, OPC UA provide synchronization;
- Virtual model (Digital Twin Model);
- Simulates the behavior of the robot (kinematics, dynamics, and environment);
- Analysis and optimization (AI/Simulation Layer)

Uses AI/ML or mathematical models for: predictive maintenance, trajectory optimization, adaptive control Feedback (Control Loop)

Commands generated by the digital twin are returned to the physical robot.

Main applications are related to maintenance, Motion optimization, Virtual testing Training algorithms.

1.3. Digital Twins in Surgical Robotics

In surgical robotics, a digital twin is a personalized virtual model of a patient + robotic system used to plan, simulate, and assist surgical interventions [5]. Figure 1 shows Digital Twin in Surgical Robotics.

A typical example is systems such as the da Vinci Surgical System [6], where digital twins can improve precision and safety.

Such a system is characterized by: Patient Data; High accuracy and low latency; Integration with medical data, Real-time control and simulation.

Main components:

- **Surgical robot** (Master–Slave System). The surgical robot is a Master Slave system that is designed to perform surgical procedures with high precision and safety, where it is possible to scale movements, overcome tremor in the surgical hand, follow a given trajectory with high precision without affecting healthy tissue, and perform movements that are difficult for the surgical hand
- **Medical Sensors and Imaging.** Sensors - related to the measurement and digitization of physiological and system parameters. Included sensors, analog-to-digital conversion, noise filtering, time series synchronization, and data preparation for real-time processing. Sensors provide a reliable data stream with minimal latency and high accuracy.
- **Patient Digital Model** (Anatomical Twin). An anatomical twin is a virtual model of the patient's body, created through high-end simulations and real-time data that used for monitoring, analysis and optimization in medicine. This technology allows doctors to study the outcome and adapt interventions to the patient.
- **Physiological Models.** Mathematical and/or simulation description of the dynamics and autonomic regulation, and allows for increased realistic signals and responses under different conditions and loads. Models support the implementation of training scenarios and provide a controlled environment for experimentation and training without risk to the patient
- **Simulation/AI module for surgical robots.** Implements modeling, simulation, AI-based training [7].

Some of the main functions of the simulation module based on artificial intelligence are:

1. Physical and biomechanical simulations - Modeling of tissues, organs and interaction with instruments; Realistic deformations of tissues (soft tissue simulation) Physics-based simulators

2. Synthetic data generation (Synthetic Data) - Simulations that generate large volumes of data for training AI and Use images such as depth data, point clouds

3. AI models for surgical assistance Behavior cloning (learning from expert surgeons) Reinforcement learning for optimization of actions, Computer vision for tissue recognition and instrument tracking

- **Surgeon interface (HMI/VR/AR).** The surgeon interface in robotic surgery systems with digital twins implements the “human-in-the-loop” concept and provides interaction between the doctor and the digital environment. . The interface provides visualization (Visualization Layer), control interface (Control Interface, Haptic Feedback) and Intelligent support (Decision Support) [8].
- **Force Feedback Control** allows the surgeon to extract information about the course of the operation in addition to visual and with the help of resistance during the procedure.

The surgeon interface transforms traditional control into intelligent, visual and tactile interaction. The surgeon interface and the simulation/artificial intelligence module are the main components of robotic systems based on digital twins. The surgeon interface provides visualization, intuitive control and real-time feedback through modern technologies such as VR/AR and haptic systems. In parallel, the simulation and artificial intelligence module allows for physically based modeling, synthetic data generation and intelligent decision support. The two interfaces form a closed system that improves surgical precision, enables preoperative planning, and supports adaptive intraoperative decision-making.

Figure 2 illustrates the architecture of a robotic surgical system with a digital twin, integrating a surgeon interface and an AI-based simulation module.

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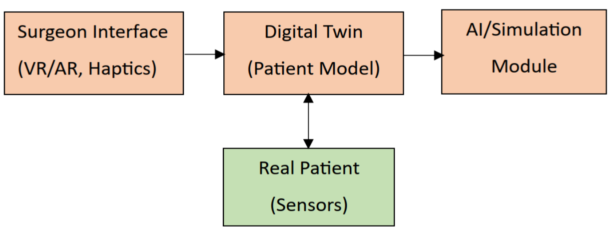

Fig. 2. Architecture of a robotic surgical system with a digital twin, integrating a surgeon interface and an AI-based simulation module.

1.4. Digital twins for training in surgical robotics

The entry of new technologies into medicine also requires excellently prepared specialists who know clinical protocols and are able to work with medical devices and adequately interpret the results obtained.

Development of telemedical robotics and remote monitoring, in which medical specialists must interpret clinical indicators and the principles of operation of digital systems.

Integration of artificial intelligence and digital technologies. support the analysis of information, but require knowledge for proper use and assessment of the reliability of the results.

The introduction of new technologies into medicine also requires highly trained specialists who know clinical protocols and are able to work with medical devices and adequately interpret the results obtained [9, 10]

Development of telemedical robotics and remote monitoring, in which medical specialists must interpret clinical indicators and the principles of operation of digital systems.

Integration of artificial intelligence and digital technologies support the analysis of information but require knowledge for proper use and assessment of the reliability of the results of training.

AI performs baseline assessment and supports.

The Surgeon performs Preparative Planning and Operative Guidance in surgical training systems.

The Robot performs operative guidance of the medical devices and processes.

A Trainee is a medical staff who diagnoses or performs therapeutic tasks.

Competency assessment includes the actions of the trainees, which are registered as input events to the system.

In robotic systems-based training, an important place is also occupied by the Patient Interface – the interaction between the learner and the "real or virtual" environment. Visual, tactile and/or functional interaction channels and safety and communication mechanisms are associated with the medical devices or robot.

- **Medical Devices** provide measurements and functionalities typical of clinical practice and allow training in conditions close to the real working environment, including working with interfaces and protocols.
- **Sensors** – related to the measurement and digitization of physiological and system parameters. Includes sensors, analog-to-digital conversion, noise filtering, time series synchronization and data preparation for real-time processing. Sensors provide a reliable data stream with minimal delay and high accuracy.
- **Real-Time Control module**, which executes closed-loop control and feedback algorithms, processes input data from sensors, compares the current state with set values or set goals and generates control signals to the actuators.
- **Executive devices and Actuators** – implement the output actions of the system. They simulate physiological responses or control real mechanical/electronic components; they convert control commands into measurable effects on the training environment.
- **Physiological Models** – mathematical and/or simulation description of dynamics and autonomic regulation, and allow the generation of realistic signals and responses under different conditions and loads. The models support the validation of training scenarios and provide a controlled environment for experimentation and training without risk to the patient.
- **Scenario Engine & Assessment** – The Scenario Module manages the logic of training situations, including parameterization of clinical cases, escalation of complications and adaptation of difficulty. The assessment component analyzes the actions of the learner, defined criteria and generates quantitative and qualitative performance indicators. This allows for objective feedback and tracking of progress over time.

2. DIGITAL TWIN-ASSISTED SURGICAL ROBOTS

2.1. System Architecture

A multi-layered architecture of a robotic surgical system based on digital twins is proposed, where the action of the digital twin is similar to a large system consisting of three main parts:

The physical object/system/process: the real element that we want to observe, reproduce and analyze (machine, robot, human body, etc.).

The virtual object/system: The digital copy generated in software that interactively reproduces the behavior and current state of the real object.

The connections between the two: which is expressed in the IoT Sensor Infrastructure, the communication (wiring, radio frequency, laser, wireless networks), the data protocols and the platforms that allow the exchange and continuous synchronization of information.

Fig. 3 presents a simplified architecture of a digital twin, including signal acquisition, processing, metric extraction, modeling and applications

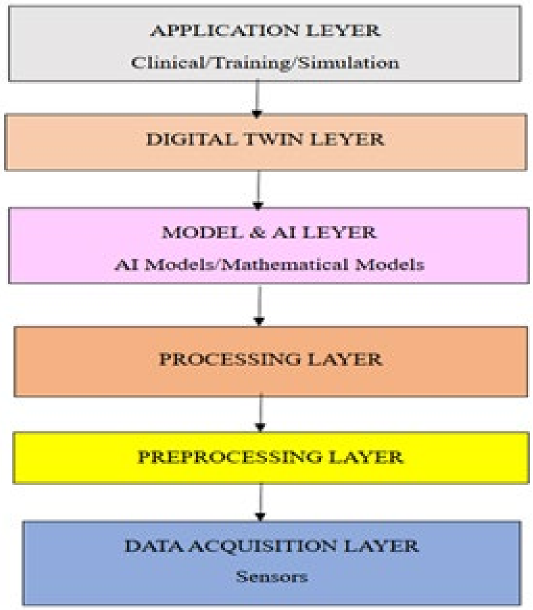

Fig 3. Simplified architecture of a digital twin.

A digital twin is a virtual model that simulates and reproduces. Its main purpose is to provide continuous synchronization between the physical patient and the virtual system for the purpose of analysis, prediction and training.

A typical architecture includes the following layers:

- Data Acquisition Layer,
- Collection of information,
- Processing & Modeling Layer,
- Extraction of some metrics and building a mathematical or AI model,
- Digital Twin Layer,
- A virtual model that simulates a physiological state, allows prediction and training,
- Application Layer.

The effectiveness of the digital twin depends on a set of technologies for collecting, processing and transmitting data in real time and generating interactive models:

Internet of Things (IoT): Intelligent sensors and devices collect data from the surrounding environment and send them to digital platforms.

Cloud computing and big data tools are used to store and analyze the data generated in real time. This allows for scaling computing capacity, correlating variables, and unlocking the potential of artificial intelligence

Artificial intelligence (AI) and machine learning: Intelligent algorithms interpret patterns from the collected data and can, for example, predict failures, recommend process corrections, detect anomalies, or predict future scenarios with high reliability.

Visualization and monitoring platforms: Through 3D systems, augmented reality (AR), virtual reality (VR), interactive systems, they allow for monitoring the current state of a specific object and simulation studies.

Taken together and properly integrated, the above tools make the digital twin a powerful weapon for analysis and optimization of processes, robotic systems, and surgical robotics.

3. SIMULATION SCENARIOS BASED ON DIGITAL TWINS FOR SURGICAL ROBOTICS

3.1. Meaning and Types of Simulation Scenarios

Simulation scenarios based on digital twins for surgical robotics enable realistic adaptive environments for training, planning, and intraoperative support [11-13].

Simulation scenarios drive the logic of the robot, including parameterization of clinical cases, the maximum point of possible complications, and adaptation to the given command. The command evaluation component analyzes the surgeon's actions against defined criteria and generates quantitative and qualitative performance indicators. This allows for objective feedback and tracking of performance over time.

3.2. Types of Simulation Scenarios

Preoperative planning- Digital twins allow for the representation of precise patient anatomy so that surgeons can explore different intervention strategies and optimize surgical trajectories. Advanced simulation models can predict tissue deformation and possible surgical outcomes.

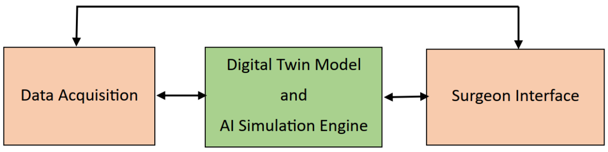

Fig. 4. Digital twin-based surgical simulation workflow.

Training and skill assessment- Simulation platforms based on digital twins and virtual reality provide a realistic environment for surgical training. These systems support objective assessment of surgical performance

Intraoperative assistance-Intraoperative - can operate in parallel with real surgical procedures, offering predictive insights and decision support. By continuously synchronizing with real-time data, these systems can anticipate complications and assist in optimizing robotic actions.

Emergency scenarios- Simulation of rare or high-risk events (e.g., hemorrhage, unexpected tissue response) allow surgeons to develop rapid decision-making skills. These scenarios are particularly valuable for training in minimally invasive and robotic-assisted procedures where errors can have significant consequences.

The digital twin-based surgical simulation workflow is shown in Fig. 4.

3.2. Use Case Diagram of Digital Twin-Assisted Surgical Interaction

A full scope of possible use cases for the tools that will be used in Digital Twin-Assisted Surgical Interaction

Figure 5 Use case diagram of a digital twin–assisted surgical interaction system showing the relationship between the surgeon, the digital twin modeling module, and patient-related surgical actions.

An UML diagram was designed by authors [14] and to generate Use Case Diagram of Digital Twin-Assisted Surgical Interaction, a source recommended by ChatGPT (OpenAI) was applied, and then the diagram was generated with the PlantUML diagram generation tool.

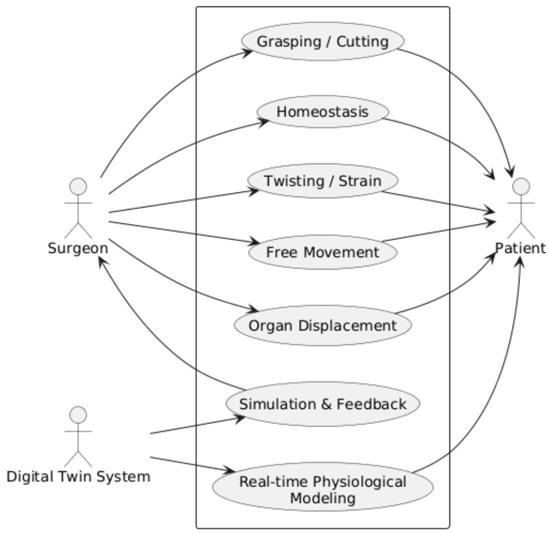

Fig. 5. Use Case Diagram of Digital Twin-Assisted Surgical Interaction.

Use Cases include Homeostasis monitoring Grasping/Cutting, Organ displacement, Free movement, Twisting /strain, Real-time physiological modeling and Simulation & feedback:

- The surgeon performs the main actions such as Grasping/Cutting, homeostasis, tension, strain, and displacement of the organ;
- Digital Twin simulates the impact on the organ;
- The model updates the state of the Patient.
- The system returns feedback to the surgeon or training simulator.

The diagram shows that the actions of the surgeon are modeled and analyzed by the digital twin, which is connected to the patient. The advantage of these diagrams is that they can be used in all simulators based on virtual and augmented reality, allowing animation of 3D models.

Another advantage of the proposed diagram is its application in Training and skill assessment and Intraoperative assistance Simulation Scenarios.

4. APPLICATIONS AND BENEFITS

4.1. Preoperative Planning

Digital twins are specific virtual models based on multimodal data, including medical imaging (CT, MRI) and physiological signals. These models allow surgeons to simulate multiple procedural scenarios before intervention, optimize surgical strategies, and assess potential complications.

Such models in preoperative planning significantly improve surgical precision and decision-making in complex and high-risk procedures. Digital twins support personalized and precision medicine, where treatment strategies are based on an individual patient profile.

Studies have examined the role of simulations and digital twin frameworks in transforming preoperative planning into a data-driven and predictive process [15].

4.2. Training with simulators (surgical simulators)

High-quality simulation environments with safe and repeatable training without risk to patients are the result of the use of digital twins in simulators. Realistic and adaptive training scenarios are created in systems that combine virtual reality (VR), augmented reality (AR), and physiological modeling.

Digital twins simulate physiological responses of the patient, providing learners with the dynamics of specific data. In addition, modern simulators include real-time feedback mechanisms, improving skill acquisition and performance assessment.

Simulation-based training has been shown to improve clinical outcomes and reduce medical errors, making it an essential component of modern education [16].

4.3. Intraoperative support

Digital twins can function as intelligent intraoperative assistants, integrating real-time patient data with predictive computational models in robotic operating rooms. In this way, the systems improve observation, robot/surgeon navigation, and surgeon decision-making.

Digital twins in robotic operating rooms provide more complete information about the patient and the environment, contributing to more accurate and effective interventions [17, 18].

4.4. Risk Reduction and Patient Safety

One of the most significant benefits of digital twins is their ability to aid in prediction and risk reduction. By simulating different scenarios in a dynamic environment, these systems enable early identification of complications and optimization of treatment.

During surgery, continuous monitoring and predictive analysis enable the detection of abnormalities and support timely interventions. Furthermore, AI-driven models improve clinical decision-making by integrating large-scale data sets and identifying hidden patterns.

These capabilities contribute to reduced intraoperative and postoperative complications, improved patient safety, and better clinical outcomes, in line with the paradigm of high-performance and data-driven medicine [19].

5. DISCUSSION

Medical robotic systems based on Digital Twins provide a number of advantages over traditional approaches based on static models and limited feedback.

Despite the advantages, robotic systems with digital twins face several challenges such as reliable high-resolution sensory feedback, as sensitive information is crucial in surgical robotics. Another challenge is the integration of heterogeneous data sources which complicates the system. Real-time data transmission requires significant computing resources, while communication latency remains an issue, especially in teleoperated systems. Additional disadvantages include high implementation costs, regulatory restrictions, and the lack of standardized frameworks for interoperability between platforms.

The effectiveness of robotic systems based on digital twins depends on input data. High-precision sensors, real-time synchronization, and reliable communication protocols ensure that precision between physical and digital objects is maintained. Digital Twins Validation in clinical and robotic environments remains challenging due to the lack of standardized evaluation methodologies and real-world data such as developing benchmark datasets, verification, and incorporating uncertainty quantification and artificial intelligence techniques to ensure safe and reliable implementation in real-world applications [20, 21, 22, 23].

6. CONCLUSION AND FUTURE DIRECTIONS

This paper explores the role of digital twins in engineering, robotics, and, more specifically, surgical robotics. A digital twin-based architecture of a surgical system is proposed, along with simulation scenarios designed for training and supporting surgical procedures. A Use Case Diagram entitled “Digital Twin-Assisted Surgical Interaction” is developed to illustrate the interaction between the surgeon, the digital twin modeling module, and patient-related surgical actions.

The main objective of this study is to demonstrate the applicability of digital twins in surgical robotics in order to enhance simulation realism, enable the development of personalized training protocols, and improve the overall efficiency of healthcare services. By virtually testing different scenarios prior to real clinical interventions, better medical outcomes and increased patient safety can be achieved.

The results indicate that digital twins represent a key enabling technology for the advancement of modern surgical robotics. They provide real-time synchronization between physical and virtual systems, enable the simulation of complex clinical scenarios, and allow for the adaptation of surgical procedures based on patient-specific characteristics.

The application of this technology leads to increased surgical precision, reduced risk of complications, and significant improvements in the training of medical professionals through realistic simulation environments.

Future research should focus on the integration of multimodal medical data, the development of AI-based adaptive models, reduction of system latency, and ensuring data security and privacy in medical applications.

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