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RE-IMAGINING PRE-OPERATIVE CARE THROUGH PERSONALIZED SURGICAL SIMULATION USING AI-DRIVEN DIGITAL TWINS

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Abstract

Digital twin-assisted surgery refers to the use of a dynamic, patient specific virtual model that mirrored physical patient in real time to enhance surgical planning, guidance, and outcomes. We propose an AI-driven digital twin framework that combines medical imaging, deep learning segmentation, and physics-based simulation to create a patient-specific virtual model for pre-operative planning and intra-operative guidance. A two-stage neural network (2D U-Net followed by 3D V-Net) generates high-fidelity anatomical reconstructions from CT/MRI scans. These reconstructions are fed into the simulator, to emulate the digital tissues and blood flow within organs in real time. By these patient's unique biological profile are replicated, Beyond static imaging, our approach incorporates elements of the PROMSHA methodology, integrating process mining with real-time simulations of hemodynamics and tissue elasticity. This enables surgeons to conduct "infinite undo" simulations, testing multiple surgical techniques, and predicting adverse postoperative events such as bleeding or infection be-fore actual surgery begins. Although there are ongoing challenges in data interoperability and computational analysis, the integration of edge computing and 5G networks offers a promising way to enable real-time decision support. This study demonstrates how bridg-ing data science with clinical practice can optimize surgical workflows, accuracy, and enhanced surgeon training ensuring patient safety.

Keywords: *Digital Twin- Assisted Surgery, PROMSHA Methodology, U-Net/V-Net, Surgical Simulation, Edge Computing.*

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1. Introduction

The current scenario of surgical treatment is being transformed by emergence of "AI". Digital Twin-Assisted Surgery (DTAS) is an emerging concept where a dynamic, patient-specific virtual model pro-vides real-time feedback to clinicians. The concept of Digital Twin-Assisted Surgery (DTAS) integrates digital twin models within surgical workflows to en-hance planning, training, and intraoperative decision-making. Similarly, Samuelsson et al. discuss DTs in orthopedics, showing how multimodal patient data (imaging, biomechanics, genomic, sensor data) can create adaptive virtual replicas for surgical rehearsal and outcome prediction.

Prior work in healthcare process modeling provides inspiration. Salas et al. introduce the PROMSHA methodology, which combines Process Mining and Process Simulation (PM+PS) to analyze clinical workflows. PM facilitates decision-making by allowing clinicians to test ”what-if” scenarios, such as the impact of dynamic staffing or the in-troduction of new diagnostic stations. PROMSHA approach generates “As-Is” and “To-Be” models of patient processes, analogous to our use of digital twins for surgical workflows. To enable such a sys-tem, patient imaging data such as CT or MRI scans must first be processed using deep learning–based segmentation models (e.g., U-Net or V-Net) to extract anatomical structures. These segmented images can then be reconstructed into a 3D anatomical model that forms the foundation of the digital twin. The overall architecture of the proposed AI-driven digital twin pipeline is illustrated in Fig. 1.

However, creating a real-time surgical digital twin is challenging because accurate physics-based simu-lations require very high computational power. For example, modeling blood flow or tissue deforma-tion can take significant computational time, mak-ing real-time use during surgery difficult. Reduced-Order Modeling (ROM) helps address this challenge by simplifying complex physical models while pre-serving their most important behavior. This enables faster simulations and makes real-time surgical digi-tal twins more practical for clinical decision support.

2. Methodology

A. System Overview and Data Acquisition

The proposed system architecture for AI-driven digital twin surgical simulation is shown in Fig. 1. The pipeline consists of six main stages:

The proposed framework kicks off with patient-specific data gathered from CT or MRI scans, which are usually saved in DICOM format. Before diving into the machine learning pipeline, these images undergo preprocessing steps like normalization, noise reduction, and alignment. We can also bring in ad-ditional inputs, such as biosensor signals and robotic kinematic data. When combined, this rich mix of multimodal data lays the groundwork for creating a patient-specific digital twin, which is invaluable for surgical analysis and decision-making support.

B. PROMSHA-Based Process Modeling and Work-flow Optimization

Arias et al. proposed the PROMSHA methodology, that provides the necessary steps for process analysis by combining PM and PS in the field of healthcare. PM is based on event logs, that are obtained from stored data in information systems and which are used to obtain knowledge about how processes are actually executed. PS is a quantitative technique with which to estimate the performance of a process without interfering with the real environment. Its architecture is built upon the principles of Design Science Research (DSR) and follows a three-phase evolutionary path: The first phase involves the inte-gration of PM and PS in specific medical context by identifying lack of structured guides. In second phase, it identifies established methodologies in lit-erature, to form foundational logic of the twin. And in the third phase involves the iterative development and validation of the methodology through real-world case studies.

It involves healthcare experts throughout the anal-ysis process, by these PROMSHA ensures that the discovered workflows accurately represent real clin-ical practices and that simulation parameters remain medically meaning-ful.

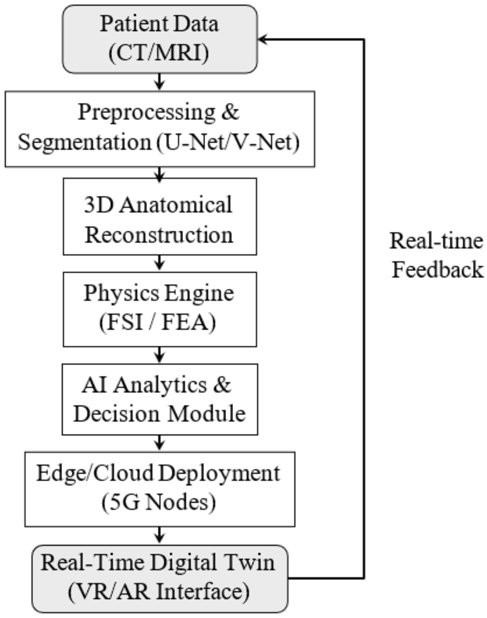

Fig. 1. Proposed architecture of the AI-driven surgical digital twin pipeline, illustrating the integration of medical imaging, deep learning–based segmentation, 3D anatomical reconstruc-tion, physics-informed simulation, and edge-enabled deployment for real-time surgical planning.

C. Deep Learning-Based Anatomical Segmentation Using U-Net and V-Net

Accurate anatomical reconstruction of patient-specific organs is essential generating a realistic digital twin of the patient. It is derived from pre-operative processes such as CT or MRI. By which Automated segmentation is achieved through deep learning (DL) architectures, performed using a two-stage neural architecture consisting of 2D U-Net and 3D V-Net.

The U-Net architecture uses an encoder–decoder structure with skip connections to preserve spatial details during image reconstruction. While 2D U-Nets efficiently process images slice by slice, they often lack full volumetric context. In contrast, 3D CNN models such as V-Net analyze entire MRI volumes, capturing spatial relationships more ef-fectively. This approach is particularly useful for segmenting complex anatomical structures like the femur, tibia, and patella and identifying imaging biomarkers for conditions such as osteoarthritis.

For precise segmentation, we turn to the KiU-Net architecture. Traditional architectures such as U-Net may strug-gle to capture very small structures due to larger receptive fields in deeper layers. KiU-Net addresses this by focusing on fine edge details while the U-Net branch captures larger anatomical struc-tures. This improves seg-mentation accuracy for small vascular or neural features, preserving anatomical fidelity in the digital twin model.

D. Reduced-Order Modeling (ROM) for Real-Time Physics Simulation

To enable real-time interaction, we utilize Proper Orthogonal Decomposition (POD) and Singular Value Decomposition (SVD) to streamline full-order models into more efficient surrogates. In the realm of hemodynamics, we think of blood vessels as electric circuit components like resistors (R), inductors (L), and capacitors (C) where pressure acts like voltage and flow resembles current. These innovative hybrid numerical-AI models significantly cut down inlet pressure errors from 45% in traditional models to just 17%, allowing for real-time feedback during vascular procedures.

$$R = \frac{8\pi\mu\,\ell}{\quad}, \qquad L = \frac{\rho\,\ell}{\quad}, \qquad C = \frac{dV}{\quad},$$

where ℓ is vessel length, A is cross-sectional area, μ is blood viscosity, ρ is blood density, V is local blood volume and P is pressure.

- Resistance (R): models viscous losses (analo-gous to Ohmic resistance).
- Inertance (L): represents blood inertia and ap-pears in terms proportional to dQ/dt.
- Compliance (C): vessel elasticity, defined as the volume change per unit pressure.

E. Edge-Native Deployment with 5G-Enabled Low-Latency Communication

The last aspect of the DTAS implementation methodologies is the deployment of the digital twin as a 5G-enabled edge computing architecture. This architecture can be divided into three major layers: the physical layer (sensors/robots), the virtual twin layer (the dynamic model), and the cognitive layer (artificial intelligence/analytics). Edge computing architecture allows the analytics to be performed as close as possible to the data source (e.g., the operating room). This approach eliminates the latency that occurs when data is routed to centralized servers within the cloud computing environment. In addition, with the 5G infrastructure, synchronization between the physical patient and the virtual twin can occur every 50 milliseconds, which allows the detection of emerging bottlenecks or anomalies almost in real-time. In addition, the use of ONNX allows high-performance AI to run directly on Android-based VR headsets, ensuring that the surgeons can access real-time predictive alerts without the need to use a workstation.

TABLE I. FUNCTIONAL LAYERS AND TECHNOLOGIES IN THE PROPOSED SURGICAL DIGITAL TWIN FRAMEWORK.

Layer	Function	Tech
Physical	Data Capture	IoT, Biosensors
Network	Connectivity	5G, Edge
Cognitive	Decision Support	Neural Nets, ROM
Interface	Interaction	R/AR, Haptics

3. Results and Discussion

A. Clinical Validation in Cardiovascular and Ortho-pedic Applications

Several research works demonstrate the practical benefits of using digital twin technology in clinical environments. For example, in the domain of mon-itoring for the application of ECMO, the potential of hierarchical digital twins has been demonstrated for the purpose of precisely predicting physiological parameters, thereby ensuring a low root mean square error (RMSE) for different physiological parameters. Some of the parameters for which the accuracy has been demonstrated include diastolic blood pressure, heart rate, oxygen saturation, and CO2 concentra-tions. Similarly, for the domain of orthopedic surgeries, the accuracy of implant sizing has been demonstrated to be as high as 97-99% using AI-assisted 3D surgical planning. Compared to the traditional two-dimensional method, the accuracy is much higher.

Fig. 2 presents a conceptual comparison of surgi-cal workflow efficiency between traditional planning methods and digital twin-assisted approaches.

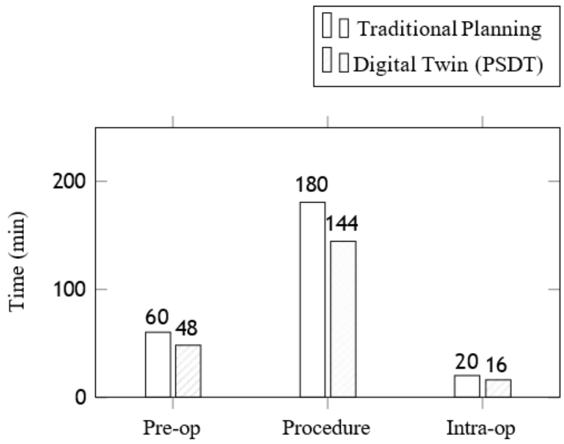

Fig. 2. Conceptual comparison of surgical workflow efficiency between traditional planning and patient-specific digital twin approaches.

B. Computational Efficiency of Reduced-Order Models

One of the major advantages of digital twin frame-works is the ability to perform high-speed simulations through reduced-order modeling (ROM). Stud-ies using Proper Orthogonal Decomposition (POD)-based ROM techniques have shown substantial re-ductions in computational time while maintaining high accuracy. For example, simu-lations that previ-ously required hours using full-order physical models can be reduced to seconds using ROM approaches while preserving over 99% accuracy in certain do-mains. In cardiovascular simulations, neural-ROM approaches have demonstrated near real-time infer-ence speeds suitable for intraoperative decision sup-port.

TABLE II. COMPARISON OF MODELING APPROACHES USED IN DIGITAL TWIN SIMULA-TIONS.

Model	Latency	Application
FEM	High (> 5 min)	Pre-op planning
DL (U-Net)	Low (~ 100 ms)	Image segmentation
PINN	Very Low (< 125 ms)	Real-time simulation
ROM	Very Low (< 50 ms)	Hemodynamic

C. Infrastructure and Network Performance

The effectiveness of the contribution of 5G tech-nology and edge computing to the mitigation of the effects of latency is verified through network simu-lation and telesurgery milestones. With the advent of the application of autonomous management of the 5G or 6G network, the application of digital twin technology has reduced the incidents of system downtime by 7%. Additionally, the application of the technology for the management of the 5G or 6G network has reduced the level of latency by 22%. With the application of edge computing for the management of the 5G or 6G network in the healthcare industry, the edge computing market is estimated to grow from a value of 9.71 USD billion in 2026 to a value of 23.22 USD billion by 2031. With the application of edge computing for the management of the 5G or 6G network in the healthcare industry, the ability to process information in a period below a millisecond is seen as crucial for AI imaging and intensive care unit monitoring while the application of edge computing eliminates the effects of

D. Challenges and Limitations

Despite these advances, however, the road to widespread adoption of Digital Twins in Healthcare (DTAS) is hindered by a lack of interoperability and semantic consistency. Perhaps the greatest technical hurdle facing widespread adoption is the lack of standardized data frameworks. An evaluation of the current state of mapping coverage between FHIR and the Observational Medical Outcomes Partnership Common Data Model (OMOP CDM)—two of the most widely used data standards—revealed that only 74% of FHIR elements could be reliably transformed into a usable format. The remaining 26% of elements, which in many cases represented critical structural differences, hindered the digital twin's ability to fully interpret patient history from disparate systems.

Furthermore, a scoping review of Human Digital Twins in healthcare found that only 35.3% of studies were able to achieve full integration into clinical workflows. The remainder of existing Digital Twins are static in nature, designed to address a singular research question, and not integrated into a continuous digital thread of data from diagnosis through recovery. Ethical concerns surrounding data privacy and equity in a global healthcare system also exist, especially in light of the high capital costs of edge-native 5G infrastructure, which could further exacerbate healthcare disparities in developed and developing systems.

Finally, it is worth examining the psychological effect of "infinite undo" in a digital twin approach to surgical simulation. While technically "infinite undo" is enabled through saving work files or using Dis-tance Fields, the psychological effect of this approach is far more relevant. It is the sense of security it gives to surgeons in training, ensuring that no operation is ever truly destructive, and thus removing the fear of consequence that prevents surgeons from fully engaging in "what-if" scenarios, thereby increasing their overall dexterity in a clinical setting.

4. Conclusion and Future Work

Digital Twin-Assisted Surgery (DTAS) represents a promising direction for precision surgical care by integrating medical imaging, AI-based segmentation, and real-time simulation. This work presented a con-ceptual framework that combines PROMSHA-based workflow modeling with Reduced-Order Modeling (ROM) to enable efficient and responsive surgical digital twins. The proposed architecture demonstrates how patient-specific models, sup-ported by edge com-puting and 5G connectivity, can enhance surgical planning, training, and clinical decision support.

However, for DTAS to reach its full potential, several translational gaps must be addressed. Future work should focus on:

- Semantic Interoperability: Developing unified platforms to improve mapping between hetero-geneous medical data standards.
- Autonomous Context-Awareness: Integrating AI-driven systems to manage surgical workflows and postoper-ative monitoring through wearable sensors.
- Advanced Physics Integration: Extending ROM techniques with fluid–structure interaction (FSI) models for more accurate simulation of vascular and cardiac dynamics.
- Edge-Native Scaling: Leveraging edge comput-ing, federated learning, and emerging 6G networks to enable scalable and real-time digital twin deployment.

Despite these advances, several challenges remain before DTAS can be widely deployed in clinical envi-ron-ments. Future research should focus on improving interoperability between healthcare data standards, incorporat-ing more advanced physics-based models such as fluid–structure interaction (FSI), and devel-oping scalable edge-native infrastructures for real-time deployment. Addressing these challenges will help enable reliable, patient-specific digital twins that support safer and more personalized surgical interventions.

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