AI-Enhanced Robotic Telesurgical Digital Twins For 6G and Beyond

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***Abstract*—Robotic telesurgery digital twins (RTDTs) are introducing a revolutionary experience in the surgical domain. It goes beyond traditional telesurgery approaches and targets immersive supervised surgical environments in rural areas that lack expert surgeons. In the light of intelligent Internet of Medical Things (IIOMT) and 6G capabilities, RTDTs will move from theory to practice. We aim to provide an overview of the role of 6G AI approaches, such as Deep Neural Networks, Reinforcement Learning (RL), and Federated Learning (FL) in delivering a new vision of robotic telesurgery using digital twins. Starting from the motivation behind RTDTs, the RTDT system architecture, and the potential of AI-6G approaches to tackle the existing challenges of RTDTs.**

I. Introduction

As we move towards the Industry 5.0 revolution, digital twin (DT) technology gains significant interest across various domains including aerospace, agriculture, smart cities, manufacturing, supply chain, smart transportation, and healthcare. DTs seamlessly integrate a wide array of technologies, including the Internet of Things (IoT), edge computing (EC), deep and reinforcement learning, extended reality (XR), 3D modeling, tactile internet, haptic communication, and 6G and beyond networks.

The convergence of artificial intelligence with the transformative capabilities of 6G technologies [1] aims to establish a paradigm of reliable surgical intervention. AI enhances surgical precision through real-time data analysis, facilitating prompt decision-making during telesurgery, and leveraging the ultra-low latency and high-speed data processing of 6G networks. This collaboration ensures continuous transmission of high-fidelity patient data, minimizing delays and disruptions.

The AI-operated 6G networks will efficiently manage network resources like bandwidth and computing power, enabling real-time decision-making. AI-driven 6G networks learn and adapt independently towards enhancing the system performance and facilitating predictive maintenance to reduce downtime and increase system availability. AI enables cognitive radio systems to autonomously adjust, improving resource utilization. RL algorithms such as Q-learning optimize resource allocation in dynamic environments. Deep learning forecasts network performance and Fuzzy logic handles uncertainty in network optimization.

II. Robotic Telesurgery Digital Twins (RTDTs)

The surgeon can perform the entire operation using an identical digital twin of the surgical robot on a digital replica of the patient's body, with tactile feedback, instead of relying solely on visual information from 3D cameras. Fig. 1 illustrates the system architecture of robotic telesurgical digital twins, where two distant surgical zones are connected via a 6G network for high-speed data transfer. The first zone includes medical staff, the patient, and the physical surgical robot, while the second zone features digital twins of the patient and robot, controlled by the surgeon via a console unit.

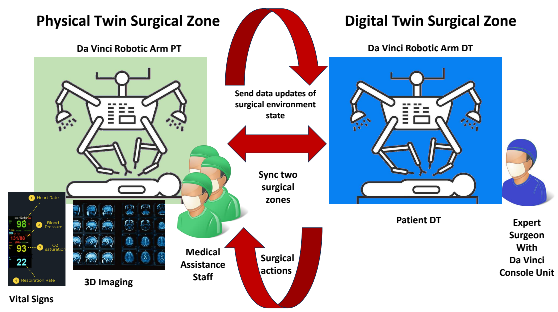

Fig. 1. Robotic Telesurgery Digital Twin Architecture

III. 6G meets AI for robotic telesurgerical digital twins

As the existing telesurgery solutions face challenges in terms of high data rates, large bandwidth, and minimum latency demands, the next generation of 6G communication technology is expected to provide crucial infrastructure for robotic surgery systems. We will introduce our vision towards deploying AI techniques for intelligent 6G networks of RTDTs systems. The predominant AI solutions in the 6G era, such as reinforcement learning (RL), federated learning and deep neural networks will be discussed in this section due to their pivotal potential in the development of RTDTs.

A. Deep Neural Networks

During the surgical procedure, RTDTs execute several intelligent services that require high-density computing, large bandwidth throughput, and ultra low-latency response which are provided through 6G networks. However, The dynamic rapid changes of 6G networks between physical and digital worlds can easily lead to network congestion or failures. DNN will serve as powerful technique in optimizing various aspects of 6G networks by enabling dynamic resource allocation for surgical digital twins, prediction of network traffic patterns, and autonomous network management, ensuring adaptability to changing connectivity status in real-time. As a result, the quality of service parameters such as latency, throughput, and reliability will be controlled by dynamically prioritizing traffic based on the RTDT application requirements and preferences [2]. Moreover, DNNs will contribute in optimizing spectrum utilization through predictive analysis of channel conditions, identification of available spectrum bands, and dynamic bandwidth allocation based on bandwidth requirements and quality constraints to guarantee uninterrupted surgical procedure.

B. Reinforcement Learning

Reinforcement learning emerges as a paramount paradigm that enables intelligent agents to adapt and optimize decision-making in real time [3] during remote surgical procedures. By iteratively learning from and interacting with the surgical environment, the RL agent learns optimal policies, takes actions based on the current state, and receives immediate rewards or penalties. RL proves more efficient than traditional control-based schemes by maximizing long-term rewards, enhancing precision, and responsiveness to dynamic challenges like latency fluctuations and network disruptions. RL-based solutions hold promise for supporting RTDTs by ensuring secure surgical data transmission, reliable real-time decision-making, intelligent resource allocation and task offloading, and dynamic network slicing.

1) Secured Surgical Data Transmission: In the context of secure data transmission, reinforcement learning can play a pivotal role in proactive threat detection and response, identifying anomalous patterns or potential cybersecurity breaches during surgical data transmission between the physical and digital twins realms.

2) Intelligent Resource Allocation and Task Offloading: In robotic telesurgery digital twin environments, optimizing resource allocation and task offloading is crucial. Bandwidth allocation ensures real-time transmission of video feeds, sensor data, and control signals between surgical sites and remote surgeons. Allocating computing resources like CPUs and GPUs supports complex algorithms for image processing and robotic control in real-time. Optimizing energy consumption extends battery life for uninterrupted operation during lengthy procedures. Effectively addressing these scenarios enhances efficiency and reduces surgical risks. For instance, a deep reinforcement learning (DRL) solution dynamically adapts to network conditions, ensuring efficient resource allocation and enhancing reliability and responsiveness during real-time surgical interventions over 6G networks.

C. Federated Learning

Modeling robotic telesurgical digital twins encounters barriers due to the vast amounts of data transmitted between surgical zones, which are hindered by data heterogeneity, diverse data acquisition methods, and concerns regarding privacy and security [4]. Real-time interaction between patient and robotic arm digital twins and their physical counterparts necessitates frequent communication between both sides.

Federated learning (FL) is as a distributed machine learning paradigm that addresses these challenges by excelling in training private and heterogeneous data. FL operates by training a model using local computing resources and device data, and then aggregating trained model parameters on a central server. This eliminates the need to centralize various data forms and classification models required to assemble a digital twin, ensuring patient privacy and data security [5].

In an RTDT system, sensor data such as heart rate and surgical robot connectivity is sent to a federated learning layer for processing. This layer handles data cleaning and rectifying missing or imbalanced values. However, data accumulation in local models can strain resources, potentially delaying communication between patients and remote surgeons. Integrating 6G networks with federated learning addresses these issues. With ultra-low latency and high data rates, 6G networks reduce delays in transmitting information between physical and digital twins. This collaborative approach spreads the computational load among network nodes, reducing the risk of performance degradation. Consequently, combining 6G networks and federated learning improves communication efficiency in remote surgical settings, leading to more timely interventions and better healthcare outcomes.

IV. Conclusion

The advanced capabilities of AI-driven digital twins empower surgeons by providing immersive training experiences and allowing them to refine their skills within a virtual, error-free environment. We propose leveraging reinforcement learning, deep neural networks, and federated learning to address the connectivity and resource allocation challenges inherent in RTDTs. This integration of intelligent surgical robots and robust 6G networks contributes to a holistic solution where patient safety is prioritized, and the potential risks associated with telesurgical procedures are significantly mitigated.

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