Edge Computing Empowered Tactile Internet for Human Digital Twin: Visions and Case Study

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***Abstract*—Tactile Internet (TI), with the capability of providing multisensory haptic human-machine interactions, is envisioned as a key enabling technology for an emerging application, called human digital twin (HDT). HDT is expected to revolutionize the human lifestyle and prompts the development of Metaverse. However, the realization of HDT poses stringent demands on pervasive connectivity, real-time feedback, high-fidelity virtual modelling and ultra-high reliability (between physical and digital spaces), which can hardly be met by TI only. In this article, we thus shed light on the design of edge computing empowered TI (namely ECoTI) for HDT. Aiming at offering strong interactions and extremely immersive quality of experience, we introduce the system architecture of ECoTI for HDT, and analyze its major design requirements and challenges. Moreover, we present core guidelines and detailed steps for system implementations. In addition, we conduct an experimental study based on our recently built testbed, which shows a particular use case of ECoTI for HDT in physical therapy, and the results indicate that the proposed framework, i.e., ECoTI, can significantly improve the effectiveness of the system. Finally, we conclude this article with a brief discussion of open issues and future directions.**

I. Introduction

THE development of Tactile Internet (TI) is reshaping the way that human-machine interacts. By integrating a variety of advanced sensors with communication and computational equipments, TI can transmit human skills through networks and provide multisensory haptic feedbacks, enabling users to interact with objects more intuitively [1]. With such features, TI is envisioned as a key enabling technology for an emerging application, called human digital twin (HDT) [2].

HDT for each individual consists of a pair of physical twin (PT) and virtual twin (VT). Specifically, the VT in digital space can replicate its corresponding human body in physical space, i.e., PT, and can also reflect the PT's status both psychologically and physiologically in real time. HDT is expected to perform as a hyper-realistic and hyper-intelligent testbed for far-reaching fields, ranging from healthcare to intelligent transportation. For example, HDT may be implemented to plan and assist complex and high-risky surgeries, where doctors can remotely observe patients' physiological indicators, operate medical equipments, conduct accurate treatments and perform various tests via physical-virtual synchronization. Such an application obviously requires strong interactions and extremely immersive quality of experience (QoE) among PTs and VTs, and has to be supported by time-sensitive multi-modal data transmitted over networks. While TI can help transmit visual-haptic data information, such as force and gesture signals sampled by tactile gloves along with video streams rendered by virtual reality (VR) devices, critical for the precise evaluation of intricate operations [3], TI itself can hardly meet HDT's stringent demands in terms of pervasive connectivity, real-time feedback, high-fidelity virtual modelling and ultra-high reliability. Fortunately, edge computing empowered TI, namely ECoTI, may be a promising solution to overcome all these limitations [4].

a) TI may experience frequent service interruptions due to limited network resources. Edge computing can potentially address this issue by providing pervasive and agile connections. On one hand, it supports large-scale data collections, real-time processing and analysis for TI, enabling data-driven HDT applications. On the other hand, it employs distributed and collaborative approaches to optimize resource allocations, improving the availability, scalability and fault tolerance of TI.
b) TI may be inefficient and vulnerable when facing with heavy traffic loads, inducing delays and inconsistencies in feedbacks across different data modalities (e.g., video, audio and tactile). Edge computing can potentially address this issue by improving the network transmission efficiencies and qualities. Specifically, data processing and analysis can be transferred from the remote cloud to edge servers closer to data sources and terminals. This reduces the distance and time required for transferring TI data over networks, and ensures effective collaboration and management of HDT while maintaining information consistency, integrity and security.
c) From the perspective of high-fidelity virtual modeling, although TI may well interconnect HDT's digital and physical spaces, PT-VTs are diffcult to be seamlessly exchanged and dynamically synchronized. Edge computing can potentially address this issue by establishing data models over multiple dimensions. In the modeling dimension, edge computing can manage, analyze, mine and integrate multi-source data collected from physical entities, enabling real-time updates and interactions of TI data. In the service dimension, edge computing can

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utilize computing and processing power of edge server to achieve high-precision simulation and modeling, providing desired functions and services, such as human activity detection and medical image analysis, according to specific HDT user and application requirements.

In summary, to be capable of offering strong interactions and extremely immersive QoE, integrating edge computing with TI in HDT applications is not only attractive but also worthy to be carefully studied. The main contributions of this article are to provide a bold, forward-looking vision on designing ECoTI for HDT, and are summarized as follows:

- We propose a novel system framework, i.e., ECoTI for HDT, aiming to provide HDT with strong interactions and extremely immersive QoE services. To the best of our knowledge, this is the first framework that manages holistic HDT functions empowered by ECoTI, including data collection, processing and transfer.
- We rigorously analyze key design requirements and challenges of implementing ECoTI for HDT, and present the key steps and core guidelines.
- We show a particular case study of ECoTI for HDT in physical therapy to demonstrate the effectiveness of the proposed framework. The use case can also be considered as a design paradigm for other HDT applications that can improve human quality of life.
- We outline and discuss major open issues to inspire future research directions.

II. Framework of Edge Computing Empowered Tactile Internet for HDT

A. System Architecture

The system architecture of ECoTI for HDT consists of three domains, i.e., master domain, network domain and controlled domain, as illustrated in Fig. 1. PTs in the master domain (i.e., physical space) can initiate human skills, such as massage or acupuncture through human teleoperators and tactile terminals, to control VTs in the controlled domain (i.e., digital space), and obtain ultra-realistic feedback from the controlled domain. As the bridge, the network domain helps transmit commands and feedback signals between master and controlled domains in real-time.

1) Master Domain: Broadly speaking, PTs in the master domain can be equipped with various tactile equipments and display devices to control VTs. For example, a doctor equipped with a pair of tactile gloves can control his/her VT (i.e., virtual hands) for massaging a patient's VT in the controlled domain. The tactile feedback will be encoded and transmitted back to the doctor through the network domain. Additionally, video and audio information may be imperative in such a scenario, and thus VR glasses with headsets are also required.

2) Network Domain: The network domain supports bidirectional communication links between the master domain and the controlled domain for information exchange. Additionally, it provides fast-responsive computing services by employing edge computing for supporting strong interactions and extremely immersive QoE services.

3) Controlled Domain: A PT is digitally modelled as a high-fidelity VT located in the controlled domain, which can be regarded as a digital agent executor of the PT. After receiving commands from the PT, its VT decodes the information and executes actions indicated by the decoded information. Based on this, the VT then generates the multimodal feedback information through sensing and transmit it back to the PT through the network domain.

B. Key Design Requirements and Challenges

The key design requirements and major challenges of implementing ECoTI for HDT are discussed as follows.

1) Strong Interactions between Physical and Virtual Twins: The interactions between a pair of PT and VT typically involve information exchange in a high frequency. For instance, for the smoothness and fidelity of haptic perception when a PT switches actions rapidly, haptic information commonly needs to be updated at a rate over 1000 times per second. These strong interactions between PTs and VTs need the support of pervasive connectivity under ubiquitous mobility, real-time communication and computation with feedbacks, and privacy protection and data security for ethics and morality.

Pervasive Connectivity under Ubiquitous Mobility: For HDT, the interactions between PTs and VTs through ECoTI inherently demand the seamless connectivity. However, services may be interrupted when a PT moves to distant locations, while its VT is still hosted in the original server. Hence, the pervasive connectivity is required for guaranteeing stable and continuous TI services [5]. Nevertheless, this requirement brings several challenges. First, when the PT moves to a place with unpredictable network conditions, such as high congestions and packet loss rates, the connectivity between the PT and VT pair is hard to be established. Second, if the PT moves from an area with a low TI user density to other high-density ones, the network workload will become more unbalanced, and the topology will become more complex and difficult to manage. Third, the mobility of PT is significantly random, which depends on their subjective consciousness. All these indicate that the pervasive connectivity of PT-VT pair under ubiquitous mobility is challenging.

Real-time Communication and Computation with Feedbacks: It is intuitive that, for HDT, strong interactions between PTs and VTs require the support of real-time communications and computations. First, feedbacks from VTs typically involve massive complex and multimodal information (e.g., audio, video and tactile signals) that requires large bandwidth to be transmitted, and thus the optimal communication resource management needs to be designed. However, most of existing work devoted to the design of uplink task offloading while ignoring the downlink feedbacks [6], which results in the low quality of response. Second, if the distance between master and controlled domains is more than 150 kilometers, it is generally known that real-time communication requirements for TI can hardly be achieved [7]. This limitation hinders the application of ECoTI for HDT, such as for ultra-long-distance surgery. Moreover, edge computing nodes usually have limited computing capacity, storage space, battery life

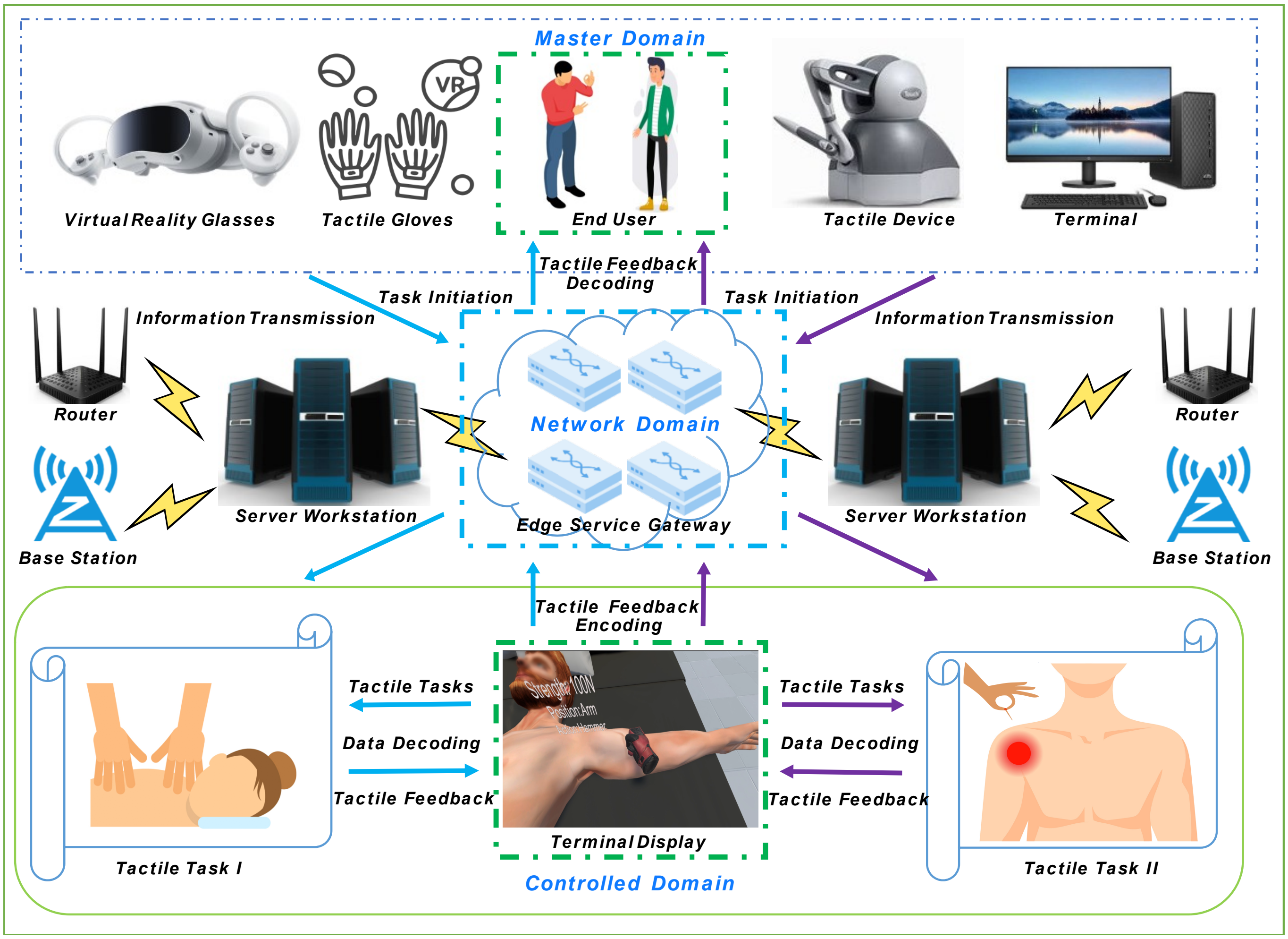

Fig. 1. System architecture of ECoTI for HDT.

and other resource constraints, and may be seriously affected by network congestions, equipment failures and attacks. These motivate the enhancement of availability, reliability, scalability and fault tolerance of edge services.

Privacy Protection and Data Security with Ethics and Morality: Massive data will be transmitted and exchanged between PTs and VTs in ECoTI during the strong interactions. Privacy protection and data security are undoubtedly required for preventing data from malicious leakages or attacks. Different from the other kinds of applications (e.g., data management in the industry), the data generated in ECoTI for HDT are human-related and highly sensitive. Any leakage of these data may result in serious ethical and moral concerns. For example, in the treatment of patients under such a framework, a large amount of individual healthcare data may be circulated. Doctors taking actions through TI for interacting with patients' VTs is vulnerable to malicious attacks on data transmission, processing and feedbacks, causing potential data manipulations and eventually the mismatch among PTs and VTs. These attacks may further lead to misjudgement, wrong decisions and failure of treatments, which are intolerable in any case [8]. Moreover, the traditional data backup, recovery, auditing schemes may not be sufficient for this application, because the operation of ECoTI for HDT has to maintain relatively stable with few jitters and service interruptions.

2) Extremely Immersive Quality of Experience: The extremely immersive QoE of ECoTI for HDT can be achieved by providing PTs with comprehensive and ultra-realistic virtual senses and actions generated by VTs. This requires the support of high fidelity virtual modeling, multimodal data analysis, and the integration of subjective and objective evaluations.

High Fidelity Virtual Modeling: High-fidelity virtual scenes of objects, tasks and actions interconnecting the master and controlled domains have to be established for ECoTI between PTs and VTs in HDT. This helps ensure interactive effects in the design of prototypes, while guaranteeing immersive QoE for users. However, the realization of such high-fidelity virtual modeling brings several challenges. First, most of the existing tactile devices (e.g., tactile gloves) have not been fully developed to capture ultra-fine-grained information, and may sometimes capture inaccurate or wrong information, making the immersive QoE being significantly degraded [9]. Second, the current virtual scene modeling via TI for offline preprocessing to deal with the system dynamics cannot be easily migrated from one server to another, meaning that it is not applicable for high mobility services with quick motion changes or scene switches. Last but not least, there is an inherent tradeoff between the sampling frequencies of tactile devices and the TI network traffics. To be more specific, the excessive sampling frequency (e.g., 1 kHZ in the remote surgery [10]) may lead to considerably high traffics occupying large bandwidths in the resource-constrained TI, and thus increasing the service latency due to potential network congestions. In contrast, the over-low sampling frequency may inevitably result in "unrealistic feeling".

Multimodal Data Analysis: Multimodal data is the fuel of ECoTI for HDT, which normally contains various types of data from multiple sources. However, the transmission and processing of such multimodal data bring several open problems. First, multimodal encoding schemes must be defined to support different modalities of TI information, without compromising the end-to-end service latency. Currently, although visual and auditory information encoding has been studied extensively, haptic encoding is still very challenging [11]. Second, the processing of multimodal data needs to be synchronous. Otherwise, cybersickness may happen. Cybersickness commonly refers to an issue that multiple sensing data (e.g., audio, video and tactile sensation) are incorporated in an interaction but the process of different sensing data are notably asynchronous (e.g., the time-lag between tactile and audio movement exceeds 1 ms) [12].

Integration of Subjective and Objective Evaluations: Unlike conventional network systems, ECoTI for HDT requires both objective and subjective metrics to evaluate the performance, including not only the service latency, reliability of communication and computation, but also the true experience of users in haptic interactions. However, it is difficult, if not impossible, to design an integrated evaluation method that can jointly capture both subjective and objective aspects, as it may involve interdisciplinary knowledge and complex models. Furthermore, compared to the objective evaluation, it is worth noting that users' feedbacks (e.g., error corrections) in subjective evaluation require much longer response time, making the real-time integration and analysis much more challenging [13].

III. Key Steps and Core Guidelines for System Implementations

To address the requirements and challenges of Section II, this section provides the key steps and core guidelines for implementing ECoTI for HDT, as illustrated in Fig. 2, consisting of component selection, tactile information encoding and decoding, edge computing and collaborative processing, auxiliary decision, and diverse feedback and evaluation.

A. Component Selection

The successful system implementation of ECoTI for HDT requires a careful selection of hardware and software components. In this regard, the first step is to select appropriate components to align with the specific requirements of the system. During the selection of these devices, special attentions have to be paid on the interface and operating environment to ensure that the system can operate seamlessly and without introducing excessive service latency. To obtain accurate tactile data, advanced haptic devices, such as Geomagic Touch [1] and tactile gloves may be utilized. To ensure low latency and high reliability in communication and computation (e.g., < 50 ms delay and $> 99.999\%$ reliability in haptic interaction-based rehabilitation [9]), tactile data and VT's status information can be distributed to nearest edge servers to speed up processing. In order to provide an immersive QoE, the scene rendering can be accomplished using the unreal engine in Unity, while VR glasses (e.g., Pico4) can be adopted to attain an immersive feeling. Finally, to guarantee the real-time transmission of tactile tasks and feedbacks, the time-sensitive networking (TSN) protocol [14] may be employed as an alternative to the traditional Ethernet for further enhancing the performance.

B. Tactile Information Encoding and Decoding

To offer strong interactive and immersive user experiences, multimodal information, such as audio, video and tactile signals, should be transmitted between PTs and VTs in HDT via TI. While audio and video information are relatively straightforward to collect, tactile information usually involves complicated multimodal data, including force area, angle and size. This complexity makes the collection, encoding and decoding of tactile information significantly challenging. To this end, deadband coding technology [3], which encodes a tactile sample only if humans can notice any changes in tactile perception, may be employed to encode the collected information into discrete values in bits for efficient transmission and data processing. The encoded information is then transmitted through the network domain to the controlled domain, where it undergoes recognition, classification and analysis to be eventually decoded. Once executed in the controlled domain, the resulting tactile feedback is collected and encoded, and in turn transmitted back to the master domain for decoding. All these complete the round-trip and closed-loop interactions.

C. Edge Computing and Collaborative Processing

The network domain is the bridge between the master and controlled domains, while the most critical node in the network domain is the edge server. A large amount of tactile information is difficult to be processed and managed locally. By enabling edge computing, users can offload the data to edge servers, and thereby reducing communication bandwidth and service delay. In real-time analysis of multimodal data, distributed and collaborative approaches (e.g., distributed computing) ensures that massive amounts of information (such as tactile and video) can be processed in parallel and effectively, resulting in high-quality results and reduced response time for tactile feedback [15]. Although the data generated in the digital space is still huge and complex, by ECoTI, the processing of HDT data can be accelerated, and a unified data management framework can be constructed.

Devices such as tactile gloves and Geomagic Touch can communicate and collaborate through wireless (Wi-Fi, Bluetooth, Cellular) and wired (Ethenet, TSN) communications, and are connected to edge nodes for alleviating their computation burdens. Each edge node determines the task offloading,

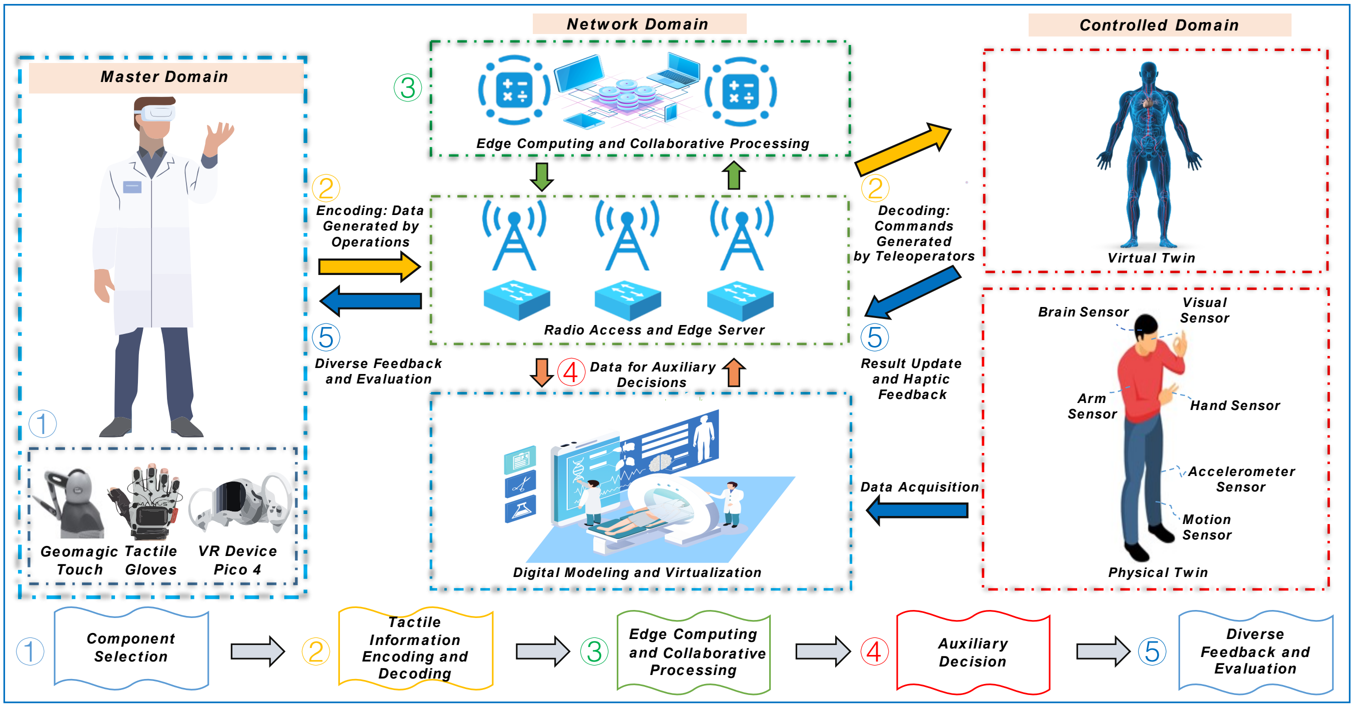

Fig. 2. Key steps and core guidelines for system implementations.

splitting and assignment according to the requirements and resource availability. The scheduler of each edge node can apply the distributed coordination to perform task collaboration based on network status, node requirements and other network conditions, and further adopt end-edge collaborative processing methods to achieve data sharing between local and edge nodes and among adjacent edge nodes, reducing the workload on a single node and improving the task processing speed. Finally, edge computing can also utilize management, orchestration, and fault-tolerance mechanisms to ensure high-quality and high-reliable services in practical implementations.

D. Auxiliary Decision

With strong interactions between each PT-VT pair in HDT, ECoTI is required to process various data on edge servers in real time. For example, the tactile information of an individual, such as human skin texture and hardness, is obtained through real-time data collection and processing. After that, the data should be analyzed to build a VT of the human body, achieving a vivid virtual representation, including its physiology, individual appearance and behavioral characteristics. In addition, to assist the judgment and treatment, ECoTI can also enable low-latency decision-making and response with real-time processing and multimodal feedback. Particularly, in massaging and hitting procedures of physical therapy, the therapist first builds a VT of the patient based on a large amount of collected historical data and update the virtual model by frequent information exchanging, then the therapist can use the tactile feedback during the operation (such as the amount of force and the texture of scalpel) to predict and correct the next action [10]. Such an auxiliary decision process can also be facilitated by edge computing and collaborative processing for gaining more powerful decision-making aids, further improving the accuracy and reliability of treatments.

E. Diverse Feedback and Evaluation

The versatility of feedback in TI, including video, audio and tactile signals, can offer extremely immersive QoE. However, depending on the context, different types of feedbacks may be produced and may cause different network overheads. Additionally, the development of effective performance metrics is also imperative. Unlike other systems, performance metrics of ECoTI for HDT should integrate both objective and subjective evaluations. On one hand, objective metrics, such as latency, jitter, throughput, reliability and motion-to-photon delay, must be precisely measured. On the other hand, subjective metrics, focusing on capturing the realism of haptic sensations, the vividness of VTs and motion sickness, have to be properly evaluated.

IV. A Case Study of Edge Computing Empowered Tactile Internet for HDT

In this section, we conduct a case study to demonstrate the effectiveness of the proposed ECoTI for HDT in a specific application, i.e., physical therapy, following the implementation guidelines in Sec. III. This can be seen as a preliminary attempt to address the design requirements and challenges mentioned in Sec. II-B, including real-time communication and computation with feedbacks, high fidelity virtual modelling, multimodal data analysis, and the integration of subjective and objective evaluations.

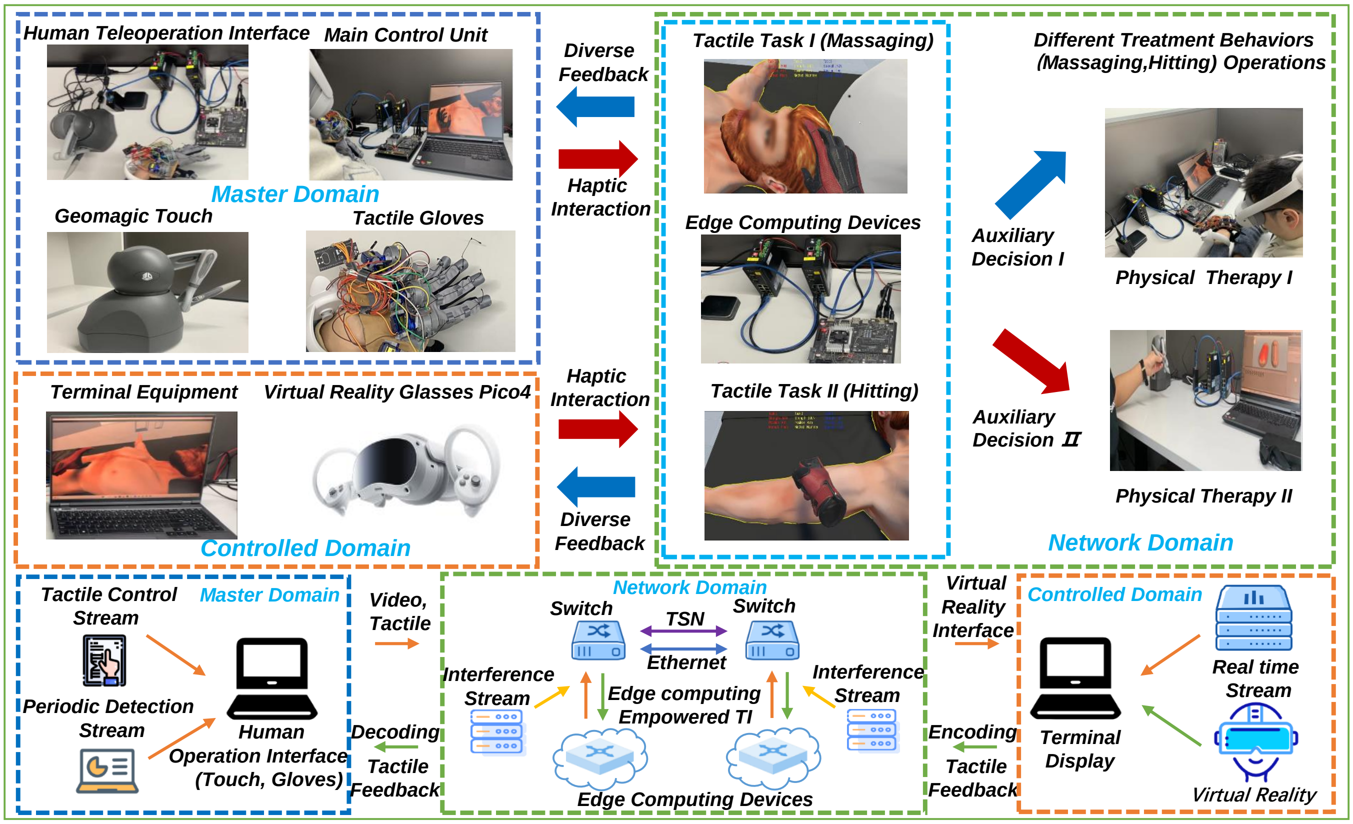

Fig. 3. A case study of ECoTI for HDT in physical therapy.

A. Experimental Setup and System Design

As shown in Fig. 3, we build a testbed platform by applying ECoTI for HDT in physical therapy, where the master domain is an agent therapist, the controlled domain is a patient, and the network domain provides both transmission and computing services. The platform considers manual therapy as the primary input. A virtual body (i.e., a VT) is digitally constructed for mapping the patient (i.e., a PT) based on the perceived user data. TI enables the therapist to provide tactile therapy actions and videos to the patient, allowing him/her to conduct high-density and highly interactive physical operations (such as hitting and massaging) according to different situations. The platform also feeds back treatment operations to the patient, letting them to experience immersive and vivid therapies.

In the master domain, a Geomagic Touch and a pair of tactile gloves are adopted to initiate the tactile operations of various kinds of massages, respectively. In the network domain, the embedded devices, including NVIDIA TX2 and Raspberry Pi, are utilized as edge nodes for processing multimodal data in real-time, while the industrial TSN switch IE4320-10s is used to construct the core network. The controlled domain consists of computer terminals and VR glasses (i.e., Pico4) for realizing the digital simulation. When the system is running, the tactile information flow will be first transmitted from the master domain to switches, and then be relayed to the controlled domain. The feedbacks (e.g., tactile, video and audio) generated from the controlled domain will be transmitted back to the master domain via TSN switches in return. Moreover, an interference stream generated randomly by Ostinato is introduced to simulate the background traffics in the core network for aligning with real-world scenarios.

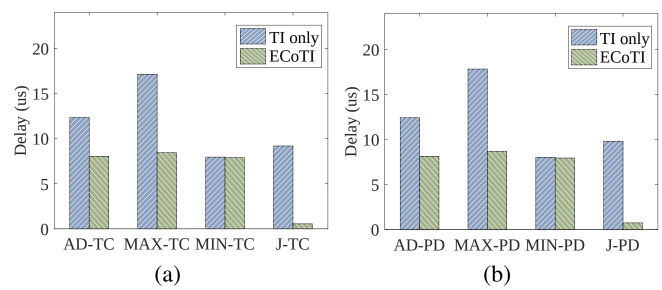

Fig. 4. An objective evaluation under two different frameworks.

TABLE I
A SUBJECTIVE EVALUATION UNDER TWO DIFFERENT FRAMEWORKS.

Framework	Video stream	Tactile feedback	Sync.
TI only	Choppy	Inaccurate	Jitter
ECoTI	Fluent	Responsive	Efficient

B. Performance Evaluation

In order to test the functions of our constructed platform, we evaluate the performance under two frameworks, i.e, i) traditional TI without enabling edge computing (namely TI only), and ii) the proposed ECoTI. We compare their performances using three indicators: a) tactile control stream delay, b) periodic detection stream delay, and c) subjective evaluation. As shown in Fig. (4a) with respect to the tactile control stream, ECoTI outperforms TI only in terms of the average latency (AD-TC), maximum latency (MAX-TC), minimum latency (MIN-TC) and jitter (J-TC). Fig. (4b) shows the results with respect to the periodic detection stream, and similarly, ECoTI has better performances in terms of the average delay (AD-PD), maximum delay (MAX-PD), minimum delay (MIN-PD) and jitter (J-PD). Furthermore, we recruit six volunteers to test the platform subjectively. As the results shown in Table I, TI only suffers from playback delays, video interruptions and asynchronous motions, while the proposed ECoTI can perform smoothly. All these indicate that, with the aim of providing strong interactions and extremely immersive QoE, our proposed framework is feasible and superior under either objective or subjective evaluations.

In summary, ECoTI leverages its flexible edge computational power and TI transmission capability to collect and process tactile feedback signals in the system for achieving real-time communication, computation and control. For the communication resource management, the optimal routing and switching strategies are employed to ensure efficient transmission of multimodal information, enabling users to experience more realistic feedback. For the high-fidelity virtual modelling, the 3D Unity and Unreal engines are respectively utilized to model and render therapy scenes, aiming to achieve vivid services and rapid scene switching. By incorporating such visual modeling and video rendering technologies, high-definition video, accurate tactile feedback and a dynamically realistic VT based on PT can be provided. In the multimodal data analysis, ECoTI adopts the fixed 1 kHz frequency deadband encoding in tactile devices, such as gloves and Geomagic Touch, to efficiently encode and reduce collected tactile signals to transmit in synchronization with the video data. Moreover, by placing computational and storage resources closer to end-users, collaborative edge computing guarantees low-latency and parallelism of multimodal data processing. To evaluate the overall effectiveness of physical therapy, subjective evaluation criteria from volunteers, along with objective measurements such as delay and jitter, are considered. The experimental results demonstrate that from the technical perspective, by employing the proposed ECoTI, our constructed platform excels in offering strong interaction and extremely immersive QoE for HDT, while providing advantages in real-world problem-solving and practical implementations.

V. Future Research Directions

In this section, we discuss several future research directions of ECoTI for HDT to potentially inspire more out-of-the-box works on this topic.

A. Predictive Haptic Interaction and Resource Optimization

Caching TI feedbacks on edge servers based on predictions during haptic interactions has a great potential to significantly reduce the HDT service latency. However, unlike traditional content caching, caching haptic signals is much more challenging because most of them are hard to be modeled, and hence impossible to be properly cached. Therefore, to ensure ultra-timely and accurate responses, advanced prediction algorithms, such as deep neural networks, along with the network resource optimization are imperative.

B. Security and Privacy with Human-in-the-Loop

Security and privacy are always critical, especially for ECoTI with human-in-the-loop. This may involve identifying potential vulnerabilities and threats in both master and controlled domains associated with data collection and processing, and the development of novel security and privacy mechanisms, such as differential privacy methods, to mitigate these risks. Moreover, legal, ethical and moral considerations corresponding to the implementation of HDT have to be taken into account.

C. Ultra-High Quality Modeling and User Experience

The profoundly immersive QoE is essential to ECoTI for HDT. Enhancing QoE may involve investigating the adoption of various AI algorithms, such as tensor holography, to personalize HDT models and applications for individual users, as well as exploring the potential for integrating multi-sensory feedbacks (beyond video, audio and tactile) into HDT interfaces to create immersive and engaging user experience. This may also prompt the development of Metaverse.

D. Edge Intelligence Enhanced Vivid Feedbacks

High-fidelity engagements and interactions require vivid feedbacks through TI. This can only be achieved if there is almost no lag (e.g., 1ms round-trip) between PTs and VTs in HDT. By applying edge intelligence, it is expected that complicated haptic interactions can be predicted, filtered, compressed and analyzed, such as using generative AI, fundamentally enhancing the performance of transmitting and processing feedback signals, and eventually guide TI to conduct active learning and self learning.

VI. Conclusion

In this article, we have presented the design of edge computing empowered Tactile Internet (ECoTI) for human digital twin (HDT). We have highlighted major requirements and challenges, particularly in the view of demanding strong interactions and extremely immersive quality of experience (QoE). We have presented core guidelines and detailed steps for implementing such a system and conducted a case study demonstrating ECoTI for HDT in physical therapy. Finally, open issues have been outlined and discussed. Overall, this work may contribute to ongoing efforts towards realizing the full potential of HDT by applying ECoTI, and pave the way for future research studies in this exciting area.

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