IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 8 July 2022, accepted 6 August 2022, date of publication 10 August 2022, date of current version 19 August 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3197900

SURVEY

QoS Provisioning: Key Drivers and Enablers Toward the Tactile Internet in Beyond 5G Era

MUHAMMAD ZUBAIR ISLAM[1], (Student Member, IEEE), **RASHID ALI**[2], (Member, IEEE), **AMIR HAIDER**[1], AND **HYUNG SEOK KIM**[1], (Member, IEEE)
[1]Department of Intelligent Mechatronics Engineering, Sejong University, Seoul 05006, Republic of Korea
[2]Department of Information and Communication Technologies, Universitat Pompeu Fabra, 08018 Barcelona, Spain

Corresponding authors: Amir Haider (amirhaider@sejong.ac.kr) and Hyung Seok Kim (hyungkim@sejong.ac.kr)

This work was supported in part by the Institute of Information and Communications Technology Planning and Evaluation (IITP) Grant by the Korean Government through the Ministry of Science and ICT (MSIT) under Grant 2022-0-00331, in part by the National Research Foundation of Korea (NRF) Grant by the Korean Government through MSIT under Grant 2022R1F1A1063662, and in part by the Strengthening Research and Development Capability Program of Sejong University.

ABSTRACT The Tactile Internet has become a revolution for Internet technology, greatly improving the transmission of skill sets (audio, video, text, and haptics) over communication channels compared with traditional triple-play data (audio, video, text). It is a strong candidate to support next-generation delay-sensitive and loss-intolerant smart applications. However, stringent requirements for the Tactile Internet, including ultra-low latency, ultra-high reliability, high availability, and ultra-security, present critical challenges to ensure Quality of Service (QoS). Consequently, several approaches have been proposed to meet these QoS requirements. This article reviews QoS provisioning approaches for the Tactile Internet. First, we present key concepts for the fifth-generation and beyond technologies, Tactile Internet, and haptic communication. Second, we discuss the Tactile Internet use cases along with strict QoS requirements. Third, we classify existing solutions, including haptic codecs, control system designs, hybrid schemes, and intelligent prediction models; provide in-depth discussion regarding these approaches to improve QoS for the Tactile Internet applications; and investigate strengths and weaknesses for each proposed solution. Finally, we present open research challenges and discuss potential future research avenues to realize the Tactile Internet services.

INDEX TERMS 5G/B5G, Tactile Internet, IoT, URLLC, teleoperations, machine learning, codecs, prediction control.

I. INTRODUCTION

The Internet has made tremendous achievements with continuous information and communication technology revolution in from First-Generation (1G) fixed Internet to Fifth-Generation (5G), and Beyond 5G (B5G) mobile Internet [1], [2], [3]. Mobile communication technologies are vital for many different life sectors, including education, healthcare, entertainment, transportation, etc.; and provide Human-to-Human (H2H) communication to exchange data using mobility devices over the Internet. Innovation in these technologies paves the way to provide Machine-to-Machine (M2M) or Device-to-Device (D2D) communication, i.e., the Internet of Things (IoT) [4]. IoT means that anything in the world can be connected anywhere and anytime, but it does not cover Human-to-Machine (H2M) communication. To deal with these limitations, IoT advancement provides a base to transfer a sense of touch and actuation in real-time to ensure successful interactions between humans and machines [5]. Fig. 1 shows communication technology evolution from H2H content to H2M steering and control communication. Internet technology from 1980s to 1990s provided simple H2H communication. Multimedia services developments during 2000s enabled wireless multimedia applications, and various researchers were developing advanced technologies, such as IoT and wearable devices, to provide M2M communication.

The associate editor coordinating the review of this manuscript and approving it for publication was Ali Shariq Imran.

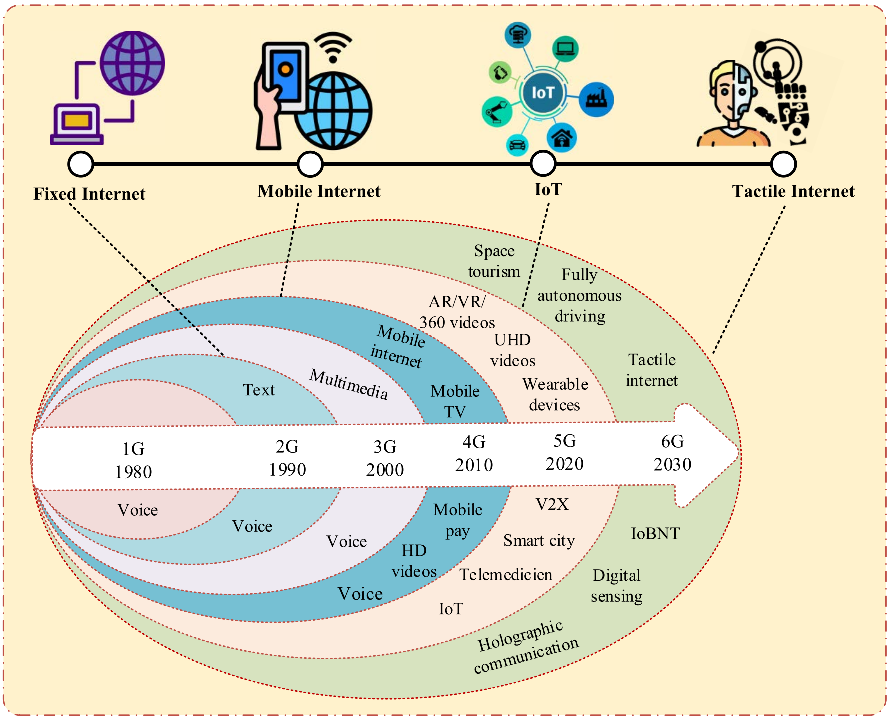

FIGURE 1. Technological evaluation of the Tactile Internet (abbreviations are defined in Table 2).

The recent technological trend is envisioning connecting human sensation for the Internet to provide H2M, opening the door for the Internet of Bio-Nano Things (IoBNT), i.e., Tactile Internet.

These technology advancements are paradigm shifts, transforming the whole world from conventional content delivery Internet to skill-set delivery Internet, introducing the Tactile Internet concept [5]. Tactile Internet enables H2M communication, where a human can interact with machines and remotely control and experience physical touching, including traditional triple-play (audio, video, and text) data in real-time over wireless channels. The concept was introduced in 2014 by Fettweis [5], where he stated that "the Tactile Internet is that communications are built for enabling steering and control, a big shift from moving only content". Thus, Tactile Internet is envisioned as next-generation IoT with various new features, including ultra-low latency, ultra-high reliability, high availability, and ultra-security to enable real-time haptic communication over 5G/B5G networks. Modern communication and network technologies (5G, IoT, and Tactile Internet) have different goals, but their requirements and features partially overlap. Fig. 2 shows the International Telecommunication Union (ITU) definitions for mobile networks (2G to B5G), IoT, and Tactile Internet [6] to help understand the Tactile Internet concept and identify commonalities between the technologies.

The Tactile Internet is considered the future Internet due to its unique characteristics, including steering and controlling physical and virtual objects in real-time via bilateral communication. Therefore, several international standard organizations have been working to refine existing and developing suitable new communication network definitions to carry haptic information with conventional traffic types. Key standard organizations, including the 3^{rd} Generation Partnership Project (3GPP), Society of Motion Picture and Television Engineers (SMPTE), European Telecommunications Standards Institute (ETSI), Institute of Electrical and Electronics Engineers (IEEE), and ITU, are working to make the Tactile Internet a reality [7], [8], [9], [10], [11]. 3GPP [7] and ITU [11] have already classified use cases into three categories: massive Machine-Type Communication (m-MTC), critical Machine-Type Communication (c-MTC), and enhanced Mobile Broadband (eMBB), along with their requirements. 3GPP defines c-MTC as Ultra-Reliable and Low Latency Communication (URLLC), providing Tactile Internet services [7]. SMPTE [8] is working on incorporating haptic information with audio-visual traffic, and ETSI is considering End-to-End (E2E) requirements and Tactile Internet application performance [9].

In contrast to these standardizations, an IEEE Tactile Internet standards Working Group (WG) [10] is investigating missing 5G and other communication network aspects to realize the Tactile Internet. Key developments and WG progress towards standardization are designated as IEEE P1918.X. The Tactile Internet baseline standard is defined as IEEE P1918.1, providing the Tactile Internet framework, including definitions, reference architecture, technical functions, and various application scenarios. Other standards under the IEEE P1918.1 scope (IEEE P1918.1.1, IEEE P1918.1.2, and IEEE P1918.1.3) focus on haptic codecs, Artificial

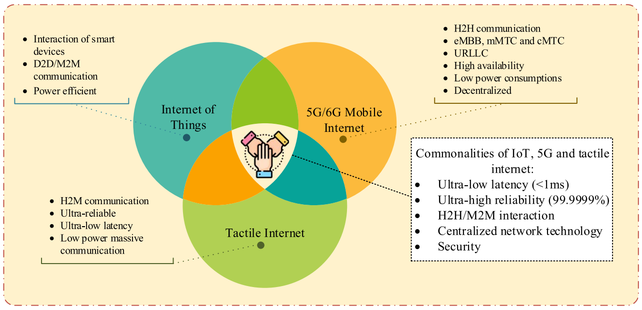

FIGURE 2. **Overlapping features and differences among concepts and technologies around 5G/B5G, IoT, and Tactile Internet (abbreviations are defined in Table 2).**

Intelligence (AI), and Medium Access Control (MAC), respectively. Standard architecture covers not only 5G, but any other communication network that satisfies E2E Tactile Internet use case requirements, including reliability, latency, availability, and security.

Compared with conventional Internet services, Tactile Internet use cases require higher Quality of Service (QoS) and Quality of Experience (QoE). Even Tactile Internet services have higher requirements, including high packet rate, less packet loss, and low latency under variable time delay to fulfill QoS and QoE requirements. Low data processing, stability control, and intelligent prediction algorithms are feasible solutions to tackle these challenges to realize the Tactile Internet. Several review papers have considered Tactile Internet, but most only consider communication network solutions to enable the Tactile Internet, with few considering data processing, stability control, and intelligent prediction solutions to provide QoS and QoE for the Tactile Internet services. This paper presents a comprehensive survey that includes current feasible data processing, stability control solutions, and intelligent prediction techniques for the Tactile Internet applications.

A. RELATED WORK AND OUR KEY CONTRIBUTIONS

Communication technologies are continuously undergoing swift evaluations to address new opportunities and challenges. As discussed in the above section, Tactile Internet is a suitable aspirant technology, and many enabling technologies offer promising candidates to realize it in practice, such as 5G/B5G, Wireless Local Area Networks, Wireless Body Area Networks, and various combinations. Recent 5G advancements towards supporting the Tactile Internet requirements under URLLC mode have promoted the technology as a critical key enabler for wireless Tactile Internet. Specifically, the work in [25], [26] explored 5G with URLLC services as a suitable solution for the Tactile Internet. Software-Defined Networking (SDN), Network Function Virtualization (NFV), and Mobile Edge Computing (MEC) were combined with 5G technology to provide suitable communication networks to achieve E2E low latency and reliability requirements for the Tactile Internet. Similarly, a brief discussion on SDN, NFV, and MEC was presented in [27], [28], and [29], where the authors' analyze the network functionalities and resources management algorithms. A comprehensive survey on 5G technological solutions and challenges were given in [30], [31]. In [32], comparative simulation analyses have been performed for Tactile Internet applications over existing technologies, such as Wireless Fidelity (Wi-Fi), WiMAX, and 3G. The comparison of the related work and our proposed survey is summarized in Table 1.

The study in [12] reviewed characteristics and comparative analysis for IoT, 5G, and Tactile Internet; and recent communication technology progress, such as long-term evolution advanced (LTE-A) to realize the Tactile Internet. The authors in [13] identify and review cutting-edge challenges and potential requirements for haptic communication and networking design for 5G-enabled Tactile Internet. The work in [14] reviewed emerging communication technologies, including SDN, NFV, and fog/edge computing, and clarified how these technologies support 5G communication to improve latency and reliability and hence enable Tactile Internet. They proposed a general network architecture design incorporating SDN, NFV with fog computing for Tactile Internet. Similarly, the study [33] proposed integrating SDN with network coding techniques to realize less packet retransmission and hence minimize network latency.

Key challenges for haptic communication over the Tactile Internet have been variously considered [15], [16], [34]. The article [34] included psychophysical and technical viewpoints to introduce the haptic communication concept and also discussed integrating video and haptic data to improve perceptual performance during haptic communication. To continue on a similar line as mentioned above, the authors in [15] and [16] reviewed haptic communication over 5G technology, while [15] focusing on strict requirements for haptic communication and reviewing various challenges and current solutions. The study in [16] explored various solutions to address haptic communication reliability challenges over 5G network infrastructure, where authors categorized the solutions into three groups: communication, data processing, and stability control solutions. Emerging Tactile Internet use cases for industrial communication were reviewed by [17]; and recent progress, including Tactile Internet system requirements, functional parameters, design challenges, and future directions, were given in [18].

In [19] discussion on fog computing to meet QoS requirements for 5G-enabled Tactile Internet were presented along with challenges and solutions for potential fog-based Tactile Internet systems to provide low-latency, high reliability, high availability, security, and privacy. They categorized the survey paper into three groups: end-user, application, and middle layer, to explore fog computing limitations for tactile applications. The study in [20] reviewed various smart applications supported by Tactile Internet, including Healthcare 4.0, Industry 4.0, Augmented and Virtual Reality (AR/VR), smart education, smart transportation, smart agriculture, etc. The authors in [21] reviewed techniques to reduce latency, focusing on resource allocation, Machine Learning (ML),

TABLE 1. Summary of existing survey articles.

		Scope							
						Comparative Analysis			
Survey	**Year**	QoS	QoE	Algorithmic Aspects	Challenges & Solutions	Haptic Codecs	Control Schema	Intelligent Prediction	**Major Contribution**
Maier *et al.* [12]	2016	×	×	×	✓	×	×	×	Discussed the recent advancement and enabling communication technologies for Tactile Internet.
Aijaz *et al.* [13]	2016	✓	✓	×	✓	×	×	×	Explore the Tactile Internet realization over role of 5G cellular networks along with technical requirements and key challenges.
Bojkovic *et al.* [14]	2017	✓	X	✓	✓	×	×	×	Highlights the critical latency requirements and presents the recent developed networking solutions to meet these requirements.
Van Den Berg *et al.* [15]	2017	✓	×	×	✓	✓	×	×	Summarize the requirements and challenges for haptic communication.
Antonakoglou *et al.* [16]	2018	✓	✓	×	×	✓	✓	×	Present haptic data communication aspects of the Tactile Internet.
Aijaz *et al.* [17]	2018	✓	×	×	✓	×	×	×	Explored the Tactile Internet for next-generation industrial communication.
Ateya *et al.* [18]	2019	✓	×	×	✓	×	×	×	Investigate the different services of the Tactile Internet along with system parameters and design challenges.
Aggarwal *et al.* [19]	2019	✓	✓	×	✓	×	×	×	Explore the fog computing based solutions for 5G-enabled Tactile Internet to meet the ultra-low latency required of the Tactile Internet use cases.
Gupta *et al.* [20]	2019	✓	×	×	✓	×	×	×	Presents the review on Tactile Internet requirements and solutions for smart application.
Yu *et al.* [21]	2020	✓	×	×	✓	×	×	×	Discuss and summarize various techniques can be employed at physical and application layer to achieve latency and reliability challenges for Tactile Internet.
Sharma *et al.* [22]	2020	✓	×	×	✓	×	×	×	Provide a comprehensive overview of the wireless Internet in term of Tactile Internet, including security and privacy challenges.
She *et al.* [23]	2021	✓	×	✓	✓	×	×	✓	Present potential to integrate the deep learning models into communication networks to improve URLLC services.
Promwongsa *et al.* [24]	2021	✓	×	✓	✓	×	×	×	Present an in-depth discussion on architecture and algorithmic aspects of Tactile Internet to overcome communication, intelligence and computation challenges.
Our Survey	2021-22	✓	✓	✓	✓	✓	✓	✓	Haptic codecs, intelligent predictions and control mechanisms contribution in QoE and QoS provisioning in Tactile Internet. Classify the Existing challenges and solution for QoE and QoE provisioning in Tactile Internet.

MEC, and cognitive radio-based technologies in 5G wireless networks to realize the Tactile Internet services. Similarly, [22] reviewed current work and proposed a wireless Tactile Internet framework over 5G/B5G communication technology, covering physical, MAC, and network layers to realize the Tactile Internet in detail.

Another recently published survey article [24] reviewed several radio resource allocation algorithms focusing on the Tactile Internet communication, intelligence, and computation challenges. They classify the exiting solutions into four clusters; (1) standard architecture and communication protocols, (2) radio resource allocation algorithms, (3) non-radio resource algorithms (lower layers), (4) non-radio resource algorithms (upper layers). Moreover, they also discuss intelligent prediction algorithms to tackle Tactile Internet intelligence challenges. However, in-depth comparative studies on intelligent prediction algorithms to guarantee QoS and QoE requirements were not presented. In [23] authors investigate the challenges and opportunities to combine the domain knowledge (i.e., optimization algorithms and theoretical tools) with deep learning frameworks to optimize URLLC. Moreover, they present numerous potential solutions on how to integrate supervised/unsupervised deep learning-based approaches into domain knowledge of communication networks in a cross-layer perspective. However, low-complexity algorithms that can be employed in real-time systems for URLLC services are still missing [35].

Although the survey papers discussed above consider architecture, methodologies, and communication-based solutions to realize the Tactile Internet; they ignored haptic codecs, control design, and intelligent prediction schemes. A more comprehensive and comparative analysis on haptic codecs, control, and AI-based prediction schemes from QoS and QoE perspectives is still missing in the literature. These constraints motivate us to present a comprehensive review of haptic codecs, control, and AI-based prediction schemes to address haptic, intelligence, computation, and communication challenges for the Tactile Internet services. Particularly, we highlight the QoS and QoE provisioning approaches that directly impact the communication network from intelligent haptic encoding, stability control (guarantee QoE) to prediction (control/feedback information). The main objective was to comprehensively review existing data processing algorithms, control designs, and prediction schemes to achieve transparency and stability for the Tactile Internet applications over the 5G/B5G communication network. The in-depth discussion on emerging use cases of the Tactile Internet in Healthcare 4.0, Industrial 4.0, Intelligent Automotive, and Comparative Driving and Teleoperations is also explored. The comparison tables are also presented to summarize different aspects of the reviewed solutions and provide insights into the provisioning approaches. Finally, we provide an empirical overview of the open research challenges and latest research incorporating weaknesses and strengths to improve QoS and QoE for tactile applications. Thus the above-mentioned technical contributions make this survey different from the existing survey articles in the literature. The main contributions from this survey article can be summarized as follows.

- We present a holistic discussion on Tactile Internet emerging use cases and classify them into five clusters, namely, Healthcare 4.0, Industrial 4.0, Intelligent Automotive, and Comparative Driving and Teleoperations, to understand the corresponding QoS and QoE critical technical requirements.
- We extensively discuss Tactile Internet fundamental challenges including haptic, intelligence, communication, and computation need to tackle to provide 5G/B5G Tactile Internet services. Moreover, we classify the existing quality assessment for Tactile Internet services, termed as Haptic Quality Assessment (HQA) metrics.
- An extensive review and in-depth discussion on the existing solution are presented and classified into three main domains, haptic codecs, control designs, and intelligent prediction schemes to improve QoS and QoE for tactile services. The challenges and possible solutions are highlighted and summarized, along with their significant technical contributions.
- The haptic databases and testbeds to test and investigate Tactile Internet stringent requirement QoS and QoE perspectives have been summarized and analyzed them and enlist their pros and cons as well.
- We identify open research challenges for developing and optimizing data processing, stability control, and intelligent prediction algorithms and present possible future avenues.

TABLE 2. Summary of important acronyms.

Acronym	Definition
H2H	Human-to-Human
M2M	Machine-to-Machine
IoT	Internet of Things
H2M	Human-to-Machine
m-MTC	massive Machine-Type Communication
c-MTC	critical Machine-Type Communication
eMBB	enhanced Mobile Broadband
URLLC	Ultra-Reliable and Low-Latency Communication
AR	Augmented Reality
VR	Virtual Reality
UHD	Ultra High Definition
V2X	Vehicle-to-Everything
IoD	Internet of Drones
QoS	Quality of Service
QoE	Quality of Experience
UAV	Unmanned Aerial Vehicle
V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure
HIC	Human Interpersonal Communication
HQA	Haptic Quality Assessment
PDb	Perceptual Deadband
PLR	Packet Loss Ratio
PSNR	Peak Signal-to-Noise Ratio
P-MSE	Perceptual-Mean Square Error
SSIM	Structural Similarity
ST-SIM	Spectral Temporal Similarity
HSSIM	Haptic Structural Similarity
CR	Compression Ratio
WKNN	Weighted K-Nearest Neighbors
GMM	Gaussian Mixture Model
GMR	Gaussian Mixture Regression

B. STRUCTURE OF THE SURVEY

Table 2 and 3 lists acronyms and notations used in this paper and Fig. 3 shows the organization of this survey article. Section II presents Tactile Internet preliminaries with a standard architecture. Section III discussed various use cases, along with principal technical requirements. Section IV discusses existing haptic codecs, control designs, and intelligent prediction-based solutions in depth. In particular, we discuss contributions from ML-based solutions to improve QoS and QoE for tactile applications. Section V discusses open research challenges and possible future avenues. Finally, Section VI summarizes the findings and concludes this survey.

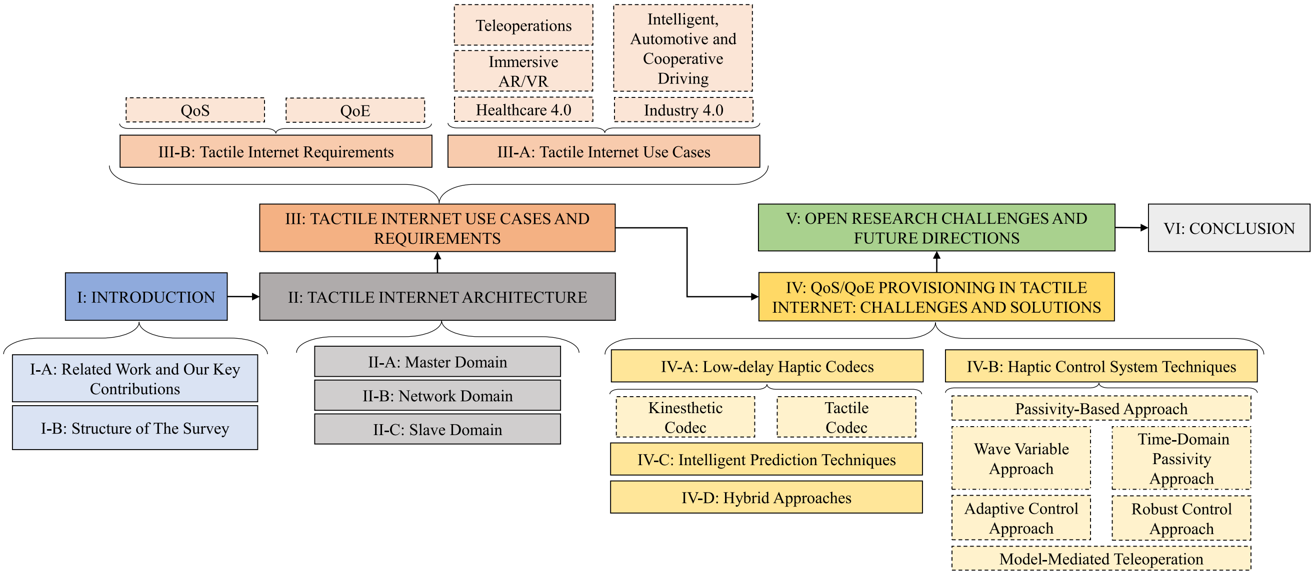

FIGURE 3. The organizational structure of the survey.

TABLE 3. List of important notations.

Notation	Meaning
d_{PHY}	Delay at Physical Layer
d_{LLC}	Delay at Logic Link Control
d_{MAC}	Delay at MAC Layer
d_c	Processing Delay
d_p	Propagation Delay
D_T	End-to-End Delay
f_m	Master Side Force
f_s	Force Feedback from Slave Side
x_m	Master Side Position Parameters
x_s	Slave Side Position Parameters
v_m	Master Side Velocity Parameters
v_s	Slave Side Velocity Parameters
b	Tuning Factor
D_1	Communication Delay in Forward Channel
D_2	Communication Delay in Feedback Channel
$u_{m/s}$	Forward Wave Transmission for Master and Slave
$w_{m/s}$	Feedback Wave Transmission for Master and Slave
E_m^{in}	Forward Channel Input Energy at Master Side
E_s^{Recv}	Forward Channel Received Energy at Slave Side
E_s^{out}	Forward Channel Energy Output at Slave Side
E_s^{in}	Feedback Channel Input Energy at Slave Side
E_m^{Recv}	Feedback Channel Received Energy at Master Side
E_m^{out}	Feedback Channel Energy Output at Master Side
α/β	Damping Elements

II. TACTILE INTERNET ARCHITECTURE

The Tactile Internet provides bilateral communication to manage touch and actuation in real-time between local (master) and remote (slave) devices with haptic and non-haptic feedback over the communication network. Haptic communication enables the Tactile Internet system to provide real-time steering and controlling objects in remote environments. In most cases, a Tactile Internet system comprises three main parts according to Fig. 4 as follows.

A. MASTER DOMAIN

The master domain comprises controllers, i.e., humans or control algorithms, that use haptic devices. If the controller is human, they interact with the device using a Human-System Interface (HSI), which converts human input into control signals. These control signals are sent to the slave domain over the network infrastructure, and the slave domain sends haptic feedback to the master domain controller to provide feedback for the human operator. Various haptic devices with multiple Degrees of Freedom (DoF) are available in the market, the comprehensive lists of the haptic devices along with vendors' details are presented in [36], [37], and [38].

B. NETWORK DOMAIN

The network domain connects the master and slave domains using different network elements to provide bi-directional communication, including routers, base stations, tactile support engine, packets, and serving gateways. Networks require high availability, high reliability, and ultra-low latency to maintain real-time steering and control. 5G communication technology is a key enabler to provide these requirements and realize tactile services, with 5G-enabled Tactile Internet architecture connecting 5G core infrastructure, e.g., base stations, with control and user plane entities.

C. SLAVE DOMAIN

The slave domain includes teleoperators or controller robots directly controlled by the master domain through control signals, hence it is also known as the controlled domain. It provides feedback to the master domain, including haptic and audio-visual signals. Master and slave domains comprise a global control loop via the network.

III. TACTILE INTERNET USE CASES AND REQUIREMENTS

A. TACTILE INTERNET USE CASES

The Tactile Internet WG [10] defines some standard use cases and their performance metrics, including teleoperation,

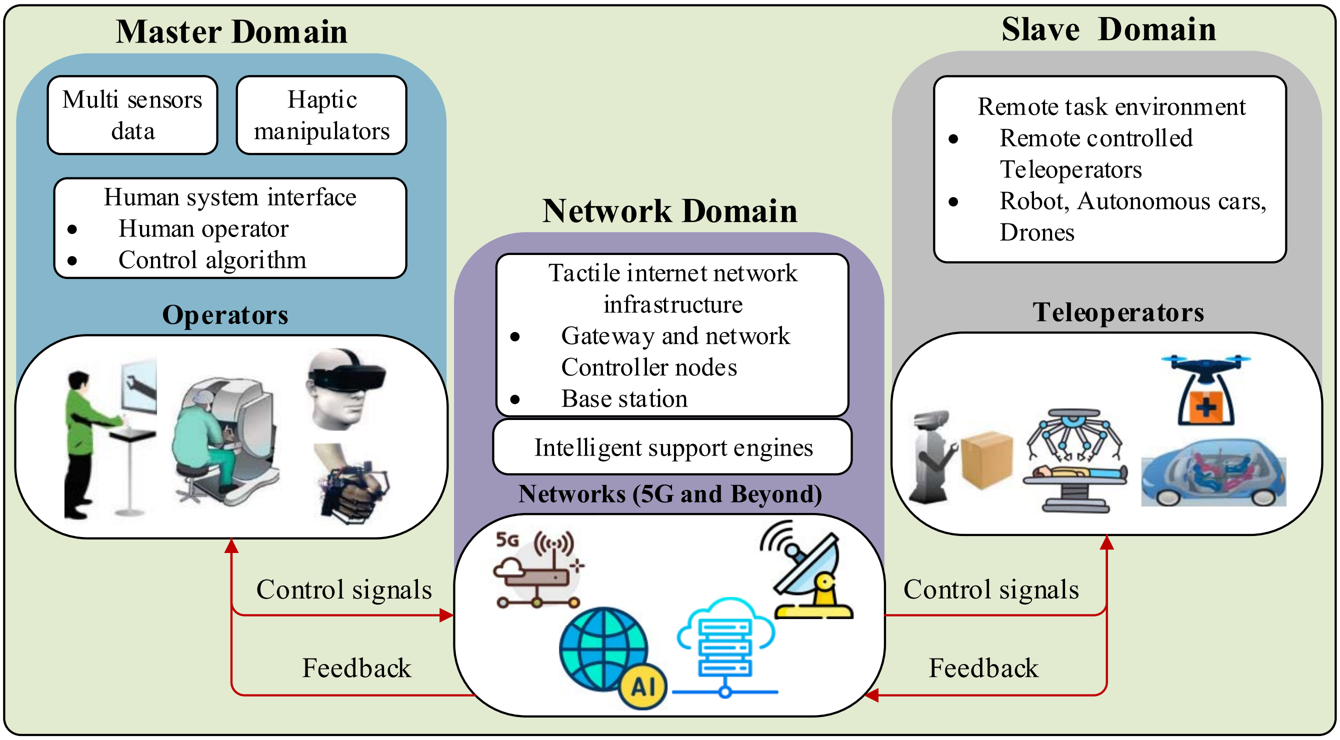

FIGURE 4. High level basic architecture of the Tactile Internet.

automotive, immersive AR/VR, Internet of Drones (IoD), interpersonal communication, live haptic broadcast, and cooperative automated driving. The work in [30] and [39] consider critical and non-critical Tactile Internet applications following [16] defined applications based on 5G key performance requirements. Fig. 5 shows the resultant use case grouping for the Tactile Internet applications based on the above-mentioned studies, where the light green circle refers to the machine operator-machine, the light cyan circle refers human operator-machine, and the light orange circle refers to the human operator-human. An in-depth discussion of these classifications technologies, along with overlapping features and differences, has been shown in Fig. 2. To illustrate the relationship between different emerging services of the Tactile Internet, the use cases are categorized into three groups, M2M (display in dark cyan), H2H (display in dark green), and H2M (display in dark orange), communication based on connectivity and interaction. The M2M part indicates the applications that are used in the M2M environment. The H2M section indicates the type of applications where real-time interaction between H2M is performed. The H2H section summarizes the emerging applications of the Tactile Internet, where humans interact with other humans at a distance via virtual environments. However, we classify the Tactile Internet use cases into five main groups: Healthcare 4.0; Industry 4.0; Immersive AR/VR;Intelligent, Automotive, and Cooperative Driving; and Teleoperations, as shown in Table 4. The teleoperation use case mostly overlaps all other use cases.

1) HEALTHCARE 4.0

Healthcare applications strongly require low latency and ultra-reliable Tactile Internet. The healthcare sector has quickly evolved from Healthcare 1.0 to Healthcare 4.0, also known as eHealthcare, which provides services including telesurgery, tele-medicines, tele-diagnosis, and tele-monitoring over the Tactile Internet that were not supported by traditional Internet structures. eHealthcare enables medical experts to be available all over the world for physical examinations, patient monitoring, or even perform complicated surgery at a distance using the remote control and telerobots. The study in [40] reviewed various telerobotic technologies in the medical domain, including telerobotic surgery and telerobotic rehabilitation; and [41] reviewed telemedicine and eHealth studies, analyzing QoS, QoE, and their corresponding clinical requirements to ensure healthcare system privacy, reliability, and stability.

2) INDUSTRIAL 4.0

Current industrial automation trends, commonly called Industry 4.0, aim to provide real-time control for the large connected systems with limited human interaction by exchanging control information over a wireless network. In contrast with traditional industry, the smart industry aims to enhance product manufacturing rate and optimize production lines by applying Cyber-Physical Systems (CPSs). Industrial automation, process automation, and remote industrial management require latency between 0.25–10 ms with

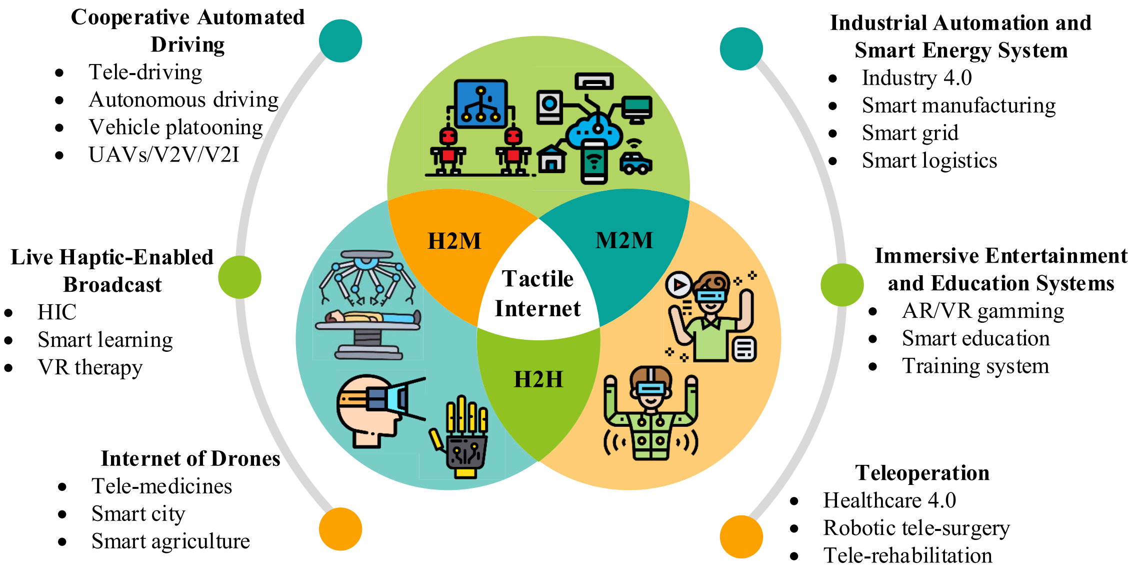

FIGURE 5. Key use cases of the Tactile Internet (abbreviations are defined in Table 2).

maximum packet failure rate $\leq 10^{-9}$. Therefore, E2E latency and reliability for industrial automation can be achieved by realizing the Tactile Internet. The work in [42] and [43] introduced interesting applications, including smart grid and smart logistics. Smart grid aims to distribute energy and monitor power generation and transmission lines; whereas smart logistics enables providing the right product quantity at the right place, time, and cost; making intelligent decisions by continuous tracking and monitoring the product supply chain. Smart grids and logistics have stringent latency and reliability requirements [44], since latency $>$ 1 ms can cause serious problems. Regarding teleoperation applications of the smart grid and logistics, we are considering process monitoring and maintenance. In the smart grid, it deals with power line monitoring, diagnosis, fault detection, and reporting via AR interaction to improve controllability. Similarly, in smart logistics, distribution processing such as packaging, metering, sorting, and labeling of the dangerous item can be done using tactile interaction [45].

3) IMMERSIVE AR/VR

Immersive AR/VR is an exciting Tactile Internet application where information from physical objects is augmented as a virtual entity in the human field. Users interact with virtual objects using AR/VR devices and perceive physical world interactions via haptic communications. This enables myriad applications, including telemedicine; VR therapy; remote education; and adaptive assistance for drivers, police, and students. It is also used for Human Interpersonal Communication (HIC) and entertainment, such as normal or serious gaming. Serious games provide motivation for learners, e.g., goal-oriented and problem-solving games. Latency $\leq$ 30–50 ms is required for most games, with some serious games requiring millisecond latency, e.g., tele-soccer ($\leq$ 1–10 ms). Increased network latency degrades user QoE for specific haptic-enabled games. The work in [46] explored VR applications for the entertainment, medical, and retail sectors. Playing music and enabling remote teaching with haptic feedback requires a latency value around 5–10 ms [30].

4) INTELLIGENT, AUTOMOTIVE, AND COOPERATIVE DRIVING

Intelligent transportation and mobility systems pave the way for autonomous driving, tele-driving, platooning, etc.; and provide services for automatic traffic flow, road safety management with the cooperative vehicle to vehicle, vehicle to infrastructure, and vehicle to any communication. Tactile vehicle to any communication provides a fast, reliable, and secure mechanism to exchange multimodal information between vehicles. Prevent accidents and making quick, complex decisions requires latency $\approx$ 1 ms with reliability $\geq$ 99.999% for autonomous driving [87]; whereas real-time traffic flow control based on local traffic and traffic light status requires 10 – 100 ms latency with $10^{-3} - 10^{-5}$ packet failure range.

Unmanned Aerial Vehicle (UAV), also known as drones, advancements have numerous real-world applications via wireless communication systems. UAVs comprise sensors connected via IoT to form the IoD. IoD low cost, high mobility, and flexibility enables various smart applications, including tele-medicine, industrial inspection, telemonitoring, tele-rescue operations, and parcel delivery, and haptic-enabled UAVs will significantly contribute to smart city development. Reference [88] described a possible UAV-enabled intelligent transportation system, and the study in [79] proposed a UAV-assisted video surveillance system that required maximum E2E latency $\leq$ 1 ms with packet loss rate $\leq 10^{-7}$. Similarly, the study in [83] and [86] discussed using UAVs for smart cities and smart farming; and [86] reviewed supply chain management challenges in the Industry 4.0 era and proposed a model for Farming 4.0 and Agriculture 4.0.

5) TELEOPERATIONS

Teleoperation systems comprise a human operator, communication channel, and teleoperator, and allow the human operator to interact with the teleoperator at a distance with real or virtual environments to execute complex operations. A bilateral teleoperation system with multimodal feedback, including audio, video, and haptic, was shown in Fig. 4, where the master device must receive feedback from a controlled device over a communication network and forms a global closed loop. Teleoperation systems can be divided into three categories depending on their architecture and topologies: unilateral, bilateral, and multilateral systems [89]. Another classification regime based on communication delay and user interaction level divides it into two key groups: mission-based and direct control systems [90], as shown in Fig. 6. Haptic-enabled teleoperation systems, also known as telehaptic systems, have various applications in medical, industrial automation, education, transportation, etc., sectors. Table 4 compares several examples of smart applications for the Tactile Internet with corresponding use case categories overlapping the teleoperation use case.

The Tactile Internet provides key network infrastructure with stringent requirements to realize various applications with real-time control. In contrast with traditional applications, haptic-enabled smart applications demand high QoS and QoE. However, the communication delay is a critical challenge to realize tactile applications and is sometimes called the 1 ms challenge. These applications require haptic sampling rates $\geq$ 1 kHz to ensure QoE and system control loop stability. QoS and QoE for the application degrade for increased network communication delay and sampling rate increases for highly dynamic environments. Moreover, each use case has demand unique key performance indicators. In the next subsection we will discuss requirements and challenges correspond to each Tactile Internet use cases.

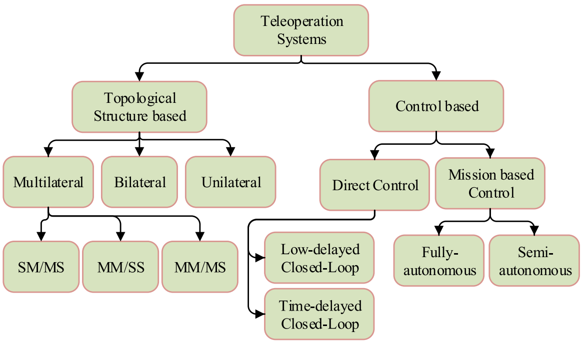

FIGURE 6. **A taxonomy of the teleopration systems based on topological framework and control design: SM/MS indicates single master multiple slaves, MM/SS is multiple Master single slaves, and MM/MS is multiple master multiple slaves.**

B. TACTILE INTERNET REQUIREMENTS

Before presenting the key technical requirements, we discuss quality assessments, i.e., QoS and QoE, we evaluate the Tactile Internet applications. The stringent technical network requirements for the Tactile Internet are listed below following [17], [25].

1) QoS

QoS is defined as service quality performance and is strongly related to network-centric communication. In terms of haptic communications, QoS parameters characterized by latency, reliability, and availability of the communication network are translated as latency, jitter, packet loss, and synchronization, respectively [91]. In a general way, QoS refers to a mechanism used by the network at each network layer to support

TABLE 4. **Applications of Tactile Internet.**

Application				Reference
Healthcare 4.0	Tele-opeartions	Tele-health	Robotic tele-surgery	[20], [40], [47]–[49]
			Tele-rehabilitation	[50], [51]
			Tele-medicines	[41], [52]
		Wearable tactile devices		[53]–[55]
Industry 4.0		Smart manufacturing		[56]–[58]
		Smart grid (monitoring or maintenance)		[42], [59]
		Smart logistics (monitoring or maintenance)		[43], [45], [60]
Immersive virtual reality		Entertainment	Gaming	[46], [61]
			HIC	[62]
		Smart education	Smart training system	[63]–[68]
			Smart learning	[69]–[71]
		Healthcare	VR therapy	[72]–[74]
Cooperative/Automated Driving/IoD		Vehicle platooning		[75]
		Intelligent transportation		[76]
		Autonomous/Tele-driving		[77], [78]
		UAVs/V2V/V2I		[79]
		Tele-medicines		[80]
		Smart city		[81]–[84]
		Smart agriculture		[85], [86]

QoE. In the literature, there are various solutions like SDN, routing techniques, cognitive radio, and queue management from application to the physical layer to support QoS. The QoS demands of Tactile Internet use cases can vary from each other depending on latency, reliability, availability, as are defined below.

- *Latency:* Network E2E latency or Round Trip Time (RTT) delay is defined as "the time taken to transfer a packet from source to destination and receive the acknowledgment information at the source" corresponding to the detailed explanations below.

$$\begin{aligned} D_T &\approx \Sigma_{i=1}^{n} d_i + d_p + d_c \\ &= \left\{ d_{PHY} + d_{MAC} + d_{LLC} + \Sigma_{i=3}^{7} d_i \right\} \\ &\quad + d_p + d_c, \end{aligned} \tag{1}$$

  where D_T is total E2E delay; d_i is delay in network layer i; d_{PHY}, d_{MAC}, and d_{LLC} denote delay at physical, MAC, and logical link layers, respectively; d_p is propagation delay; d_c is processing delay; and n indicates the total number of layers in the protocol stack model. For example, $n = 7$ for an Open System Interconnection (OSI) protocol stack because the OSI model comprises seven different abstraction layers: physical, data link, network, transport, session, presentation, and application. The Tactile Internet system requires ultra-low latency (1 – 10 ms), depending on the application type and dynamic nature of the environment. The 5G URLLC service is a promising enabler to provide ultra-low latency between master and slave domains and experience haptic sensations in real-time. The different approaches to achieve low latency for 5G-enabled Tactile Internet are compiled in Fig. 7.
- *Reliability:* Reliability is defined as the number of data packets successfully received at the destination relative to the total number of data packets sent, i.e., Packet Loss Ratio (PLR) or failure rate. Similar to latency, Tactile Internet applications require a maximum failure rate between 10^{-3} – 10^{-7}. Packet failure rate directly impacts QoE and Quality of Task (QoT) for the Tactile Internet system. It is a challenging task to achieve a trade-off between ultra-high reliability under ultra-low latency. Promising solution sets under 5G and B5G technology were given in [39], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], and [110] as illustrated in Fig. 7.
- *Throughput:* Throughput refers to the amount of data transmission from source to destination over a time interval. A next-generation application like autonomous driving requires high data throughput, where multiple sensors data are collected simultaneously. To deal with such large data volume in real-time exposes various challenges of Tactile Internet. Similarly, a haptic-enabled AR/VR application with 4K 360° video and simple holographic communication demands a data rate around 0.5 – 2 Gigabit per second (Gb/s). In Tactile Internet services, data rate depends upon the type of applications and their requirements. In the literature, there are various promising solutions, including increment in transmission frequency as listed in Fig. 7.

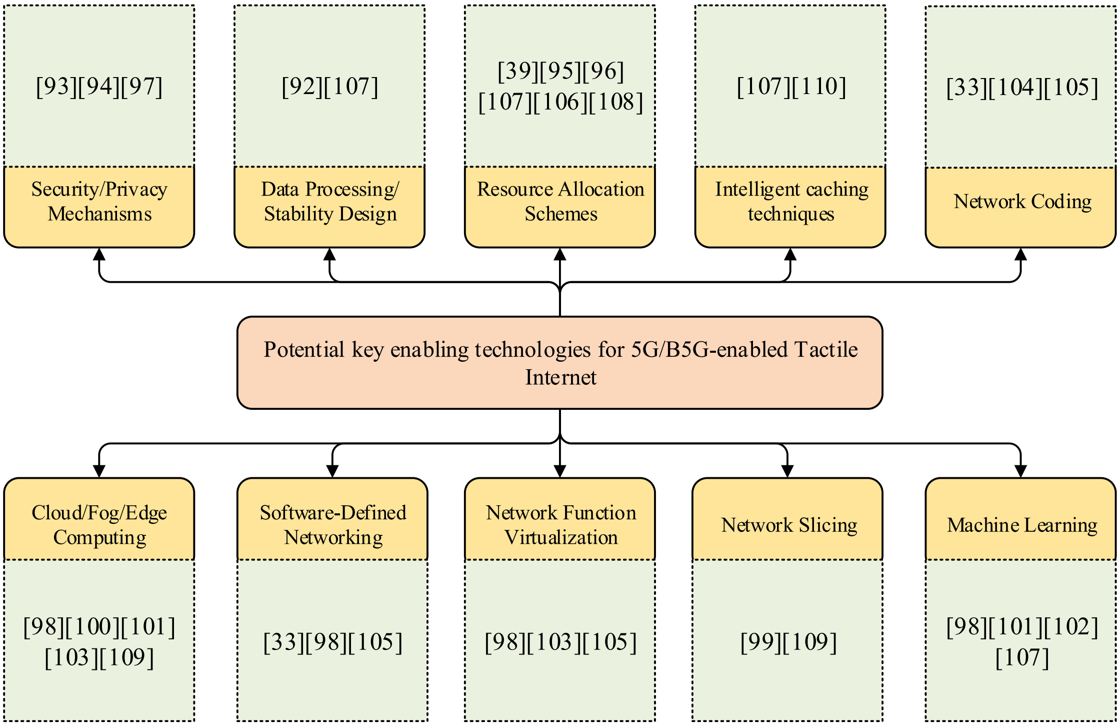

FIGURE 7. Key enabling technologies to meet 5G/B5G-enabled Tactile Internet requirements.

TABLE 5. Haptic quality assessment metrics (abbreviations are defined in Table 2).

Evaluation Metrics		
QoS	Latency	
	Jitter	
	PLR	
	Throughput	
QoE	Subjective	MUSHRT [112]
		MOS
		VTQA [113]
	Objective	PSNR
		HPW-PSNR [114]
		P-MSE [115]
		HSSIM [116]
		ST-SIM [117]
		HPM [118]
		Hybrid (SNR+SSIM) [112]

- *Availability:* The availability performance indicator explains the amount of time for which the application service remains available, and the availability of the communication service can be calculated by the following formulas [111]:

$$U = \frac{\Sigma_i \Delta t_i}{T} \tag{2}$$

$$A = 1 - U \tag{3}$$

where U is the unavailability of the service, T is the time when the service is expected to run, and the Δt_i is the length of the i^{th} down time interval over T. Finally, the communication service availability A is calculated using (3). Tactile Internet requires ultra-high availability for tactile services, considerably better than 99%, depending on application type. It is challenging to provide availability for both locally and distant tactile systems while simultaneously meeting ultra-low latency and ultra-high reliability requirements. Various solutions have been proposed to achieve the availability requirement and improve tactile service performance [39], [98], [99], [102], [106], [109].

In the literature, three main approaches have been proposed to solve these challenges: communication, data processing, and stability control solutions [16]. Fig. 7 summarizes previously proposed potential solutions improving communication networks to realize haptic applications.

2) QoE

QoE is defined as user excitement or irritation level [119], i.e., it expresses the user's experience with service, and it is more user-centric. QoE involves technical and nontechnical evaluation parameters as described in [120]. It brings together users' experiences, expectations for application, and underlying communication system efficacy. It is worth mentioning that a finite association is required between QoS and QoE to maintain QoE from QoS components [121]. QoE is subcategorized into two ways, subjective and objective. In the subjective test, some exports from the same domain are invited to score the experienced results. One of the famous QoE subjective evaluation metrics is the mean opinion score (MOS). The MOS is an absolute category rating scale that comprises a five-grade quality scale. The MOS scaling, along with the corresponding quality class description, is presented in Table 6 based on ITU-R M.1079-2 [122] and ITU-R BT.500-14 [123]. It is worth mentioning that presented values are the minimum QoS/QoE requirements; however, recent emerging application demands minimal latency (≤ 1 ms) with packet loss $\leq 10^{-7}$.

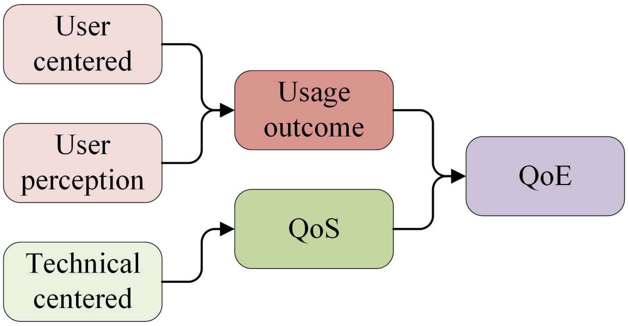

FIGURE 8. Relation between QoS and QoE.

TABLE 6. Impact of the QoS metric on QoE.

QoS			QoE			
Delay (s)	PLR (%)	Throughput (kbs)	MOS (Score)	PSNR (dB)	SSIM (%)	Quality (Class)
≤ 2	$0.0 \sim 0.2$	≥ 500	5	> 37	> 0.90	Excellent
≤ 4	$0.2 \sim 0.5$	≥ 250	4	31 – 37	0.77 – 0.89	Good
≤ 8	$0.5 \sim 2.0$	≥ 120	3	25 – 31	0.61 – 0.76	Acceptable
≤ 15	$2.0 \sim 4.0$	≥ 60	2	20 – 35	0.38 – 0.60	Poor
≥ 15	> 4.0	≤ 60	1	<20	<0.38	Bad

However, in the objective test, evaluation of the QoE is carried out based on service-related different measurement parameters (PLR, latency, jitter). Peak signal-to-noise ratio (PSNR) is an objective quality assessment technique, where maximum possible signal power and divided by the power of the distorted signals. There is a small amount of work in the literature on this type of evaluation metric regarding haptic communication. The relationship between QoS and QoE is depicted in Fig. 8, where it can be seen clearly how the QoS technical parameters (latency, jitter, PLR) impact QoE. Additionally, it shows that higher QoS does not mean that we achieve the desired QoE, although it also requires interactiveness with service and the ability to serve the desired task to the users. The work in [124] investigates the relation between QoE and E2E latency, where the authors proposed a QoE model to maximize the tactile users' QoE by optimizing the E2E delay. We summarize the existing QoS and QoE evaluation metrics in Table 5 and named them as Haptic Quality Assessment (HQA) metrics. Similarly, the impact of the QoS metric on QoE is listed in Table 6 and adopted from [125].

Table 4 shows teleoperation utilization for most haptic-driven applications. The primary aims for teleoperation systems are stability and transparency during the interaction between local and remote environments. Teleoperation transparency is defined from the ''human feeling'' point of view, where human operator impedance Z_h matches environmental impedance Z_e, i.e., $Z_h = Z_e$, where the impedance is the ratio of force to velocity. Transparency can also be defined in terms of user feelings: how well the human operator feels with haptic sensations while directly interacting with the remote environment. Teleoperation close-loop stability guarantees stable transition contact between master and slave regardless of their behavior. A critical challenge for teleoperation systems is to simultaneously ensure stability and transparency. Teleoperation systems lose significant stability and transparency for even small delay and/or packet loss, which will ultimately degrade QoE, QoT, and Quality of Control (QoC).

Therefore, this paper included low-delay data processing, control design, and intelligent prediction solutions to guarantee bilateral teleoperation system stability and transparency over various time-delayed communication networks. The following section explains the aforementioned challenges in-depth, including potential solutions.

IV. QoS/QoE PROVISIONING IN TACTILE INTERNET: CHALLENGES AND SOLUTIONS

Fig. 7 summarizes existing proposed solutions in the literature from the physical to application layer focusing on communication challenges, including radio resource allocation, protocols, multiplexing, and scheduling algorithms. Various cloud (fog/edge) computing, latency/network fluctuation prediction, and management schemes have also been proposed to ensure QoS. This survey focused on haptic codec, control design, and prediction-based solutions considering all critical tactile information challenges, including tactile packet size, packet loss, stability, transparency, etc. This section discusses potential solutions and challenges for QoS and QoE provisioning in Tactile Internet. First, we consider haptic codec schemes and compare various proposed solutions. Second, we review control design methods that enable human operators to manipulate teleoperation in a remote environment with variable communication delay. Finally, we consider intelligent predictive schemes to tackle remaining gaps to ensure the Tactile Internet QoS and QoE requirements.

A. LOW-DELAYED HAPTIC CODEC

Haptic refers to exploring objects via touch sensation and force feedback, comprises kinesthetic and tactile perceptions [126]. Kinesthetic perception is sensory information from human muscles, joints, and tendons. Information gathered from human skin using mechanoreceptors, such as surface texture or friction, is called tactile perception. An in-depth discussion on tactile and kinesthetic haptic components was presented in [126]. Kinesthetic and tactile information have quite different properties and latency requirements. Therefore, distinct codec designs are proposed for each. The IEEE P1918.1 Tactile Internet WG initiated haptic codec standardization under haptic codec task group IEEE P1918.1.1 considering these haptic classifications, providing a standardized haptic codec structure, with requirement details [120]. The group aims to develop optimal data compression schemes to exchange tactile and kinesthetic information and enable services for human-in-the-loop Tactile Internet. Therefore, it provides reference data traces, software, and hardware framework to develop and test kinesthetic and tactile codecs.

The haptic signal sampling rate must be $\geq$1 kHz to maintain global control loop stability and experience real-time haptic sensations [120]. This high packet rate induces network congestion, jitter and finally introduces an additional delay in the communication network. Given this high packet rate requirement, bilateral teleoperation systems require optimal haptic data compression and reduction technologies to stabilize communication. Table 7 compares and classifies potential data reduction and compression techniques for haptic-enabled bilateral teleoperations over the Tactile Internet to ensure QoS and QoE, where **Sig**, **Not Sig**, and **Mixed** indicate significance levels. **Sig** indicates the proposed coding scheme was simulated from standard databases provided by IEEE P1918.1.1 (haptic codec WG) and compared with one or more baseline schemes; whereas **Not Sig** refers to schemes where no standard databases were utilized, and performance evaluation did not consider any baseline schemes. **Mixed** indicates that although the proposed scheme did not utilize any standard database, it substantially outperformed baseline schemes.

1) KINESTHETIC CODEC

Kinesthetic data reduction techniques can be categorized as statistical or perceptual approaches [127]. Statistical data reduction algorithms are primarily based on lossy data compression techniques, using Discrete Cosine Transformations (DCT), Discrete Fourier Transformations (DFT), or wavelet transformations for haptic data compression [16]. Statistical data reduction focuses on compressing packet size for haptic communication over the network, whereas perceptual-based techniques reduce haptic data packet rate. Perceptual data reduction is borrowed from psychophysics and relies on a Just Noticeable Difference (JND) threshold approach. JND is also known as difference threshold that, providing a minimum threshold value where a human operator can perceive stimulus intensity changes determined from Weber's law [128],

$$\Delta I/I = K$$

where ΔI is stimulation intensity difference, and I is stimulus intensity. Weber's fraction, k, also called Weber's constant or JND, provides the upper bound for calculating haptic data sampling rate over the network. Weber's law uses the calculated threshold to reduce haptic data sampling rate over the network. Weber's law-based codec, also known as Perceptual Deadband (PDb) or PDb based coding, are standard kinesthetic codecs [120]. Fig. 9 shows PDb codec for

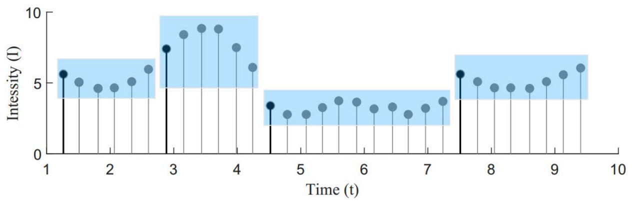

FIGURE 9. Overview of the perceptual deadband principle.

one-dimensional haptic data samples, where the black dots indicate the output of the PDb codec scheme, and perceptual thresholds by PDb are displayed in blue zones. Haptic samples that lie within PDb (blue zones) are dropped during encoding, and only perceptually significant samples are broadcast. This indicates that the change in the signals is too small to be perceived by a human. The PDb can reduce the packet rate up 80% to 90%. Other JND-based perceptual schemes use predictive coding and are employed to predict the haptic sample from haptic data [128]. Table 7 shows kinesthetic codec classification and corresponding compression characteristics. Section IV-A2 describes the detailed reason behind these classifications and Fig. 10 illustrates the current haptic codec taxonomy.

Many approaches used transform coding for the kinesthetic codec to tackle communication network impairments. Previous studies tended to focus on real-time or non-real-time use cases to design the haptic codec. This paper focuses on real-time haptic data compression schemes. The reason is that haptic traffic compression in real time helps to reduce the jitter disturbance effect from the communication network. The authors in [129] proposed a quantization approach for haptic data reduction in the communication network. DCT transforms haptic information into the frequency domain, then DCT coefficients are calculated and quantized, and finally, Huffman coding was employed to reduce the haptic data. A motion copying experiment was organized to validate the proposed method. The work in [130] proposed Wave Packet Transformation (WPT) coding from image compressing for haptic data compression for teleoperation systems. They showed the proposed codec scheme performed better than DCT and DFT in terms of buffer size, compression depth, and computational complexity. Despite the benefits, analysis shows that buffer size affects the network latency while adding extra processing delay. The authors suggest using maximum compression depth and optimal buffer size with minimum computation complexity for optimal data compression.

However, applying WPT on input signals produces distortion [131], hence a selected-DCT algorithm (sDCT) was proposed for the network control system to transmit haptic data. A bubble sorting algorithm was used to select the highest DCT coefficients based on high peak energy measures. Simulation results in the paper showed the proposed sDCT approach outperformed existing DCT, DFT, and WPT approaches. Computational efficiency using sDCT approach for haptic-enabled teleoperation systems was also superior to the other compression approaches. The aforementioned block-based compression techniques joined with transmission techniques have introduced additional delay due to the processing of blocks of the signals. There is a need for compression methods that tackle the high packet rate and network load challenge with minimum processing delay. In this regard, researchers have proposed perceptual predictive coding and a hybrid of block-based and stream-based approaches.

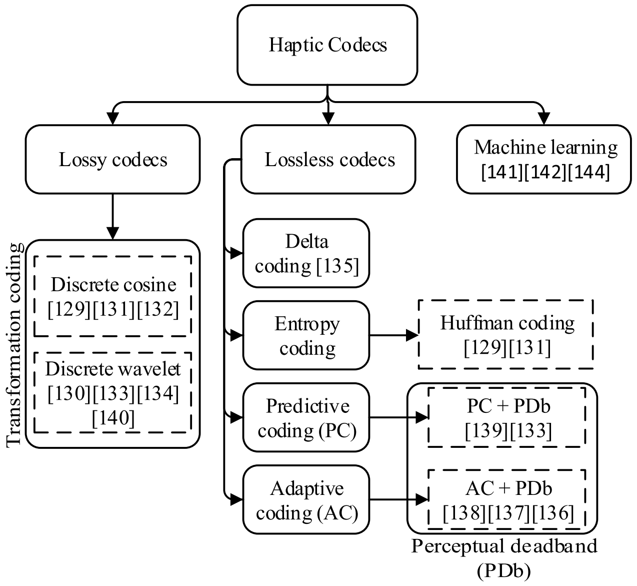

FIGURE 10. Taxonomy of the existing haptic codecs.

The authors in [132] proposed an E2E low delay Perception Lossless Codec (PLC) to meet haptic driven service requirements. The proposed PLC used Run-Length Coding (RLC) after quantifying the frequency signals, where RLC aims to remove redundant or identical values. They used a reference database [120] for fair comparisons with other strong baselines, including DCT and sDCT. The proposed scheme demonstrated better efficiency in terms of haptic structural similarity, Signal-to-Noise Ratio (SNR), transmission rate, and delay. Analysis shows that the proposed scheme achieves a 7ms encoding delay with the length of 8 samples and a computational delay of around 0.1 ms. The study in [127] analyzed different PDb approaches considering single and multidimensional kinesthetic data signals. Reference [138] proposed an Opportunistic Adaptive Haptic Sampling (OAHS) technique to achieve a high haptic packet rate and dynamically adapt haptic data signal transmission in a shared network. Parameters to tune the haptic sampling rate in the proposed OAHS scheme were controlled based on the Weber fraction to meet QoS requirements for the Tactile Internet. The authors in [137] proposed a perceptual-based adaptive sampling approach to estimate JND on real-time telehaptic data and hence reduce packet rate over the communication network. The primary objective was to update the Weber threshold in real-time following individual perception without prior knowledge and adaptively sample force signals

TABLE 7. Haptic data reduction and compression techniques for Tactile Internet. In the effect column, SIG indicates that the reference follows standard database and baseline comparison, NOT SIG indicates that the reference follows standard database without baseline comparison and mixed indicates that the reference follows baseline comparison without standard database (abbreviations are defined in Table 2).

Proposed Technique		Codecs		Improved QoS/QoE factor(s)	Effect	Major Contribution
		Kinesthetic	Tactile			
Transform Coding	DCT [129]	✓	×	SNR	Not Sig	Present a quatization technique with focus to improve haptic data compression rate.
	sDCT [131]	✓	×	CR	Mixed	Analysis different signal and multiple parameteric compression methods and present a novel haptic data compression algorithm considering selection and integration of best feature of wavelet and DCT.
	WPT [130]	✓	×	CR	Not Sig	Introduce a multiple parametric codec design to compress and improve haptic data and with a focus to overcome the network control challenges.
	PLC [132]	✓	×	SNR, HSSIM	Sig	Propose a E2E perceptual-lossless compression method to reduce coding delay, coding loss, bit rate and improve perceived quality for haptic-driven services.
	VC-PWQ [133]	×	✓	SNR, PSNR, ST-SIM	Sig	Present a highly scalable codec incorporating wavelet transformation with vibrotactile perceptual model considering both scenarios online and offline .
Analysis-by-Synthesis	SLP-based [134]	×	✓	ST-SIM	Sig	Propose a perceptual vibrotactile signal compression method incorporating DWT and sparse linear prediction coding to guarantee low bit rate with negligible distortion.
	BINBLISS [135]	✓	×	MSE	Sig	Propose a codec algorithm for real-time tactile data stream compression to satisfying haptic-driven services.
	Peak-Suppressing [136]	✓	×	MSE	Mixed	Extent the original PDb approach and propose a peak-suppressing adaptive haptic packet rate control scheme to reducing the network load.
	Adaptive Sampler [137]	✓	×	MOS	Not Sig	Propose a adaptive sampling scheme for kinesthetic samples transmission to ensure QoS for telehaptic communication.
	OAHS [138]	✓	×	SNR	Mixed	Present a adaptive scheme for telehaptic system to deal with network impairments by tuning PDb parameters in real-time.
Hybrid	PP Model [139]	✓	×	CR	Not Sig	Propose a predictive method based on autoregressive model that integrate statistical and perceptual coding concepts to improve haptic data reduction.
	PVC-SLP [140]	×	✓	SNR, PSNR, ST-SIM	Sig	Introduce the sparse linear prediction coding based vibrotactile scheme exploiting the cutaneous sensitivity function to minimize the imperceptible vibrotactile signals and improve quality.
	Data-driven Codec [141]	×	✓	SSIM	Sig	Introduce a ultra-low delayed vibrotactile codec utilizing data-driven approach to meet Tactile Internet requirements.
	EVA [142]	×	✓	PSNR/ST-SIM	Sig	Present a autoencoder design to develop compression method for haptic vibrotactile data utilizing deep NN approach with focus to minimize rate-distortion cost.

to ensure QoE. Experimental results for the proposed framework confirmed QoS and QoE improvement. However, their proposed scheme only outperformed considering a fixed set of QoS and QoE metrics, such as no communication delay stability-ensured system with no transparency impairment.

The study in [136] explored the PDb approach for haptic packet reduction and showed bursty haptic traffic problems during teleoperations, which maximized other network impairments, such as transmission delay and packet loss. They proposed a peak suppressing adaptive PDb scheme to solve this problem, dynamically controlling haptic data packet rate based on former packet transmission records and reducing transmission burstiness. A rate control algorithm was also proposed using a four-parameter logistic model to exploit PDb to stabilize packet rate. The rate control algorithm is responsible for adjusting the PDb and controlling the additional transmission delay.

Simulation results indicated the proposed scheme improved QoS compared with baseline PDb approaches for subjective and objective quality measures. The work in [92] and [128] reviewed predictive sampling for haptic signals and several predictive algorithms, focusing on realizing the Tactile Internet use cases. In [139], the authors proposed a parallel strategy Predictive-Perceptive (PP) model to reduce codec delay, as shown in Fig. 11. The PP model utilized the autoregressive model to predict future outcomes based on prior outcomes. The authors proved the proposed parallel strategy required less execution time and optimized haptic data reduction compared with the sequential version. The authors in [135] proposed a Binary Indicated Numbers with Bit-level Integrated Scalability Support (BINBLISS)

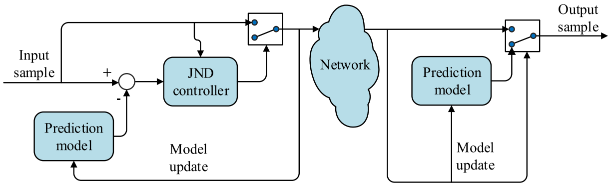

FIGURE 11. Predictive perceptive model design for haptic communication in teleoperation system via predictive sampling.

compression algorithm for real-time tactile data streaming employing delta coding. The main aim was to compress tactile data without delay. The authors argue that their proposed method adjusts the processing within the defined standard value for sensor processing (0.1 ms). BINBLISS algorithm performance advantages were proved on two datasets in terms of Mean Square Error (MSE).

2) TACTILE CODEC

Tactile codec techniques were also classified into two clusters, similar to kinesthetic codec classification: transformer coding and analysis-by-synthesis approaches [140]. These approaches aim to reduce similarities among original tactile signals. Transformer coding transforms tactile signals into a domain representation using DCT or DFT, as discussed in Section IV-A1; whereas the latter approach obtains key parameters during analysis, and tactile signals are subsequently synthesized based on these captured parameters. These tactile codec classifications are similar to the grouping for kinesthetic codec techniques. Therefore, we classified kinesthetic and tactile codec techniques into three classes: transformer coding, analysis-by-synthesis, and hybrid combining both approaches. Table 7 compares current haptic data reduction and compression approaches to improve QoS and QoE provisioning for teleoperation systems.

Several previous studies considered kinesthetic coding schemes, with emphasis to enable stable haptic communication in a teleoperation system in the presence of network impairments. However, most approaches ignored haptic communication tactile characteristics, and few studies considered tactile codecs. Most teleoperations demand both kinesthetic and tactile haptic aspects, hence optimal tactile codec schemes are essential. Therefore, we empirically reviewed and summarized existing tactile codec approaches to help make them informative for the haptic codecs design community. Vibrotactile Codecs with Perceptual Wavelet Quantization (VC-PWQ) have also been considered in [133]. First, a block unit split input signals into a block feed to the DWT, which transformed each input block into a different frequency spectrum. Second, the psychophysical model measures perceptual thresholds to reduce signal correlations. The proposed scheme achieved performance in terms of SNR and PSNR with different compression ratio (CR) over a standard data set with 280 vibrotactile samples.The results also indicate low algorithmic delay.

A tactile codec based on Sparse Linear Prediction (SLP) proposed in [134], with the main objective to optimize QoE while guaranteeing a low bit rate without reducing signal quality. They considered sparsity constraints on a predictive algorithm to model individual sensitivity information and proposed the perceptual quality assessment metric as Spectral Temporal SIMilarity (ST-SIM) to evaluate tactile coding schemes. Simulation results in terms of ST-SIM and MSE confirmed the suggested tactile codec scheme had the potential to compress vibrotactile signals. Similarly, the study in [140] extended the model [134] and proposed a Perceptual Vibrotactile Coding (PVC) based on SLP incorporating a cutaneous sensitivity model to support tactile-driven services. This hybrid approach first analyzed vibrotactile signals to capture filter parameters and then employed those parameters are to synthesize the signals. They then developed a tactile sensitive model based on four channels for perceptual quantization, as shown in Fig. 12. The proposed PCV-SLP scheme was validated via simulation on two publicly available databases, one with 280 vibrotactile signals from 9 different samples [143], the other included 1001 vibrotactile signals for 184 different sample classes [144]. Performance was quantified on both subjective and objective HQA measures.

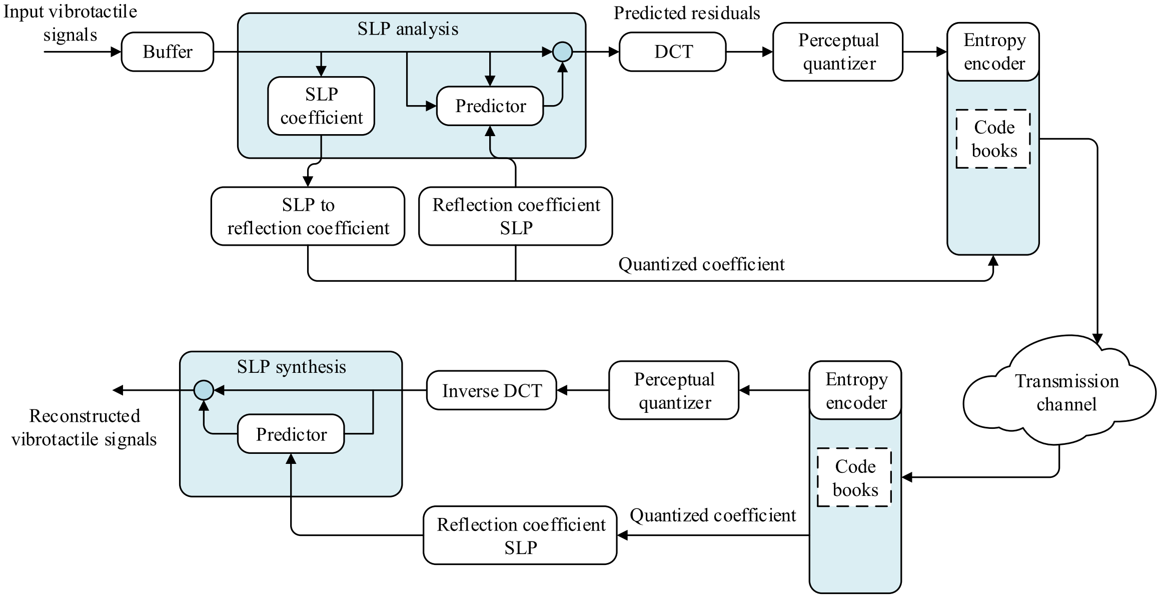

FIGURE 12. Block diagram of PVC-SLP scheme design along with encoder and decoder details (abbreviations are defined in 2).

In [141], the authors proposed a data-driven approach to reduce haptic data rate within restricted communication bandwidth to ensure QoS and QoE. The proposed coding scheme was suggested as a tool to minimize computational complexity, latency, and quality degradation. Thus, their proposed scheme considers ultra-low latency communication and computational complexity to support haptic-driven applications over 5G communication network. They experimentally evaluated compression performance for the proposed data-driven approach in terms of energy consumption. The study in [142] proposed a deep neural network-based End-to-End Vibrotactile Autoencoder (EVA) for the tactile codec to improve Rate-Distortion (RD) performance and maximize QoE. The proposed scheme aimed to optimize RD with minimum cost and E2E low coding delay. The EVA model was trained on standard data traces for vibrotactile data compression with different compression levels. Experimental results confirmed that the proposed EVA scheme outperforms PVC-SLP for all data traces in terms of PSNR and STSIM and improved RD performance.

Summary and Insights: This section presented haptic codec schemes to support the Tactile Internet services. Highly efficient and low delay codecs are essential to ensure QoS and QoE provisioning. Considered existing coding techniques for both kinesthetic and tactile feedback services included reducing packet size or packet rate and minimizing packet loss to improve QoS. Considered studies focused on trade-offs for RD and improving PSNR and other perceptual quality measures to maximize QoE.

We first described different real-time coding techniques, including lossy and lossless, and then classified existing haptic coding techniques into transform coding, analysis-by-synthesis, and hybrid approaches. We presented in-depth comparisons for quite recently proposed solutions in Table 7. The most significant insight was that previous studies focused more on kinesthetic than tactile codecs, with few research papers regarding tactile codecs compared with kinesthetic codecs. Hence, there is substantial demand for techniques to improve QoS and QoE for haptic-driven services. Moreover, there is no standard objective assessment metric to measure perceptual quality; hence work in this direction is also required.

B. HAPTIC CONTROL SYSTEM TECHNIQUES

Ever-increasing demand for teleoperations with haptic information over communication networks has encouraged researchers to investigate and focus on various stability ensuring control designs. The main objective for teleoperation system control design is to provide operator satisfaction in the presence of both latency and haptic packet loss. Therefore, designing an optimal controller with system model complexities, disturbances, parametric uncertainties, communication delay, high pack rate ($\geq$ 1 kHz) and packet loss ($\leq 10^{-9}$) is challenging. References [16], [40], [145], [146], [147], and [148] reviewed various control schemes, but none provided in-depth discussion on haptic enabled teleoperation system control solutions. The work in [16] provides an overview for different haptic-enabled teleoperation system control designs, but they did not consider ML-based control designs or intelligent prediction for haptic data. The authors in [148] reviewed recently proposed control designs but ignored haptic aspects for the communication network. In [40], the authors reviewed control design methods for medical teleoperation systems. However, they ignored control design challenges to guarantee stability and transparency. Therefore, in this paper, we present an extensive review and comparative analysis for recently proposed approved control design solutions focusing on QoS and QoE provisioning for haptic-enabled teleoperation systems.

Bilateral Teleoperation Systems Control Architecture: Section III-A5 discussed teleoperation system objectives to control remote environments and execute tasks according to operator control signals. In particular, haptic communication between master and slave manipulators requires a closed-loop over the communication network. Consequently, the global control loop makes teleoperation systems more sensitive to communication delay and packet loss. Communication delay is a critical factor for teleoperation system performance due to trade-off between stability and transparency. These communication related challenges degrade system stability and transparency and eventually reduce operator QoE. Therefore, an appropriate controller design is essential to improve teleoperation system stability and transparency. The control system aims to deliver adequate feedback on the remote task and maintain overall system stability. Teleoperation systems utilize different control architectures based upon haptic signal exchange between master and slave domains. These control architectures have been classified by their ability to compensate for communication delays and improve bilateral teleoperation stability and transparency [149].

The most generic architecture design includes Two-CHannel (2-CH) and Four-CHannel (4-CH) communication architectures. The 2-CH architecture can be four-fold subcategorized [150]. Master and slave domains utilize only one channel in 2-CH architecture to exchange bilateral communication.; whereas pairs of different channels are utilized in 4-CH architecture to exchange haptic information. Position measurements utilize two other channels and force measurements use two different channels to exchange data between the master and slave. Position and force measurements are used by both master and slave side local controllers to compensate for time delay and ensure system stability and transparency.

The study in [40], [89] introduced other possible control architectures for multilateral teleoperation systems in time delay communication networks. The current paper summarizes bilateral control teleoperation systems architectures to ensure QoS and QoE requirements, considering significant and already proven control schemes for bilateral teleoperation systems under time-varying and unknown delay to improve QoS and QoE as shown in Table 8.

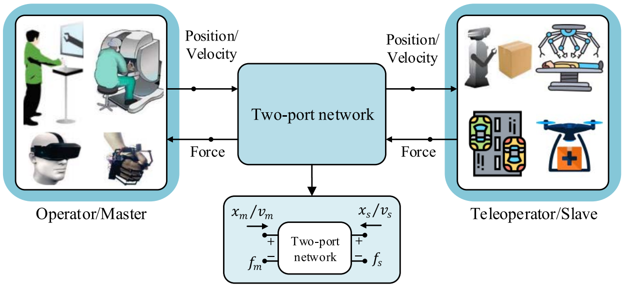

FIGURE 13. Overview of the two-port network for bilateral teleoperation system (notations are defined in Table 3).

1) PASSIVITY-BASED APPROACH

Bilateral teleoperation systems are generally modeled using the two-port network model. Fig. 13 shows energy exchanges between input and output terminals for the two-port model teleoperation system. Previous haptic-enabled bilateral teleoperation system studies has shown that communication delay introduces extra energy, causing instability and discrepancy in the closed-loop system [148]. Various approaches have been proposed to design haptic control systems over two-port networks to address instability and improve transparency.

Most current controllers are based on Passivity Control Theory (PCT) [151], which offers the vital benefit that dynamic parameters for both master and slave environments are not required to be known prior to modeling the bilateral teleoperation systems. In particular, passivity-based controllers can model unknown nonlinear and complex systems with higher DoF and have been proposed for both linear and nonlinear bilateral teleoperation systems. However, this paper only considers control designs for nonlinear teleoperation systems, since these are better related to real-world applications and complexities than linear environments. Building bilateral teleoperation systems based on PCT imposes passivity conditions for all components, which are most easily met by the bilateral teleoperation system only using passive elements that do not produce extra energy. System passivity can be expressed as

$$P(t) = \int_0^t X^T.Y \mathrm{d}_t \geq 0, \tag{4}$$

where X and Y are input and output energy for the passive control system, respectively. This, total input energy must exceed output energy for a passive system. All two-port elements must follow this passivity property to ensure teleoperation system passivity. The work in [152] showed that bilateral systems must be globally passive to guarantee stability.

Therefore, the human operator and remote environment are assumed to behave as passive for bilateral teleoperation systems, whereas the communication network is non-passive due to communication delay. Communication delay not only devastates transmitted haptic signals, but also produces extra energy. Therefore, the bilateral control closed loop does not maintain passivity and becomes unstable. The challenge is to deal with non-passivity (communication delay) to ensure overall system passivity and stability. In literature, several passivity control approaches have been proposed to overcome these challenges, including Wave Variable (WVAs), Time-Domain Passivity (TDPA), and model matching approaches. The following section presents passivity-based control solutions to improve QoS and QoE for haptic-enabled bilateral teleoperation systems, and Table 8 compares the various outputs and parameters.

a: WAVE VARIABLE APPROACH

Some earlier concepts used scattering theory under the passivity framework [153], proposing a wave variable strategy to encode velocity and force information into wave variables. The wave variable strategy extends the passivity-based controller to overcome delay problems and improve teleoperation system stability. Fig. 14 shows the overall wave variable strategy structure, which can be expressed as

$$u_m = \frac{bx_m + f_m}{\sqrt{2b}}, w_s = \frac{bx_s - f_s}{\sqrt{2b}} \tag{5}$$

where x_m and x_s are the master and slave manipulator position/velocity, respectively; f_m and f_s are operator and slave manipulator force, respectively; u_m and w_s are wave transmission from master to slave and slave to master domains, respectively; and b is a tuning factor to obtain suitable balance between wave stiffness and reflected inertia (called wave impedance). Various WVA variants have been proposed, and comprehensive details on these are provided in [154]. Although WVA exhibits passivity under unknown constant communication delay and maintains teleoperation system stability [154], it does not retain passivity under variable time delay. Thus haptic signals that carry master domain information, such as position and force on the slave domain, become distorted during variable time delay, and generating more challenges, such as position and velocity tracking and wave reflection (force reflection) [155]. In particular, variable time delay desynchronizes remote tasks, degrades position information, and forces tracking performance, eventually reducing overall teleoperation system transparency.

Many approaches have been proposed to deal with these challenges to ensure haptic-enabled teleoperation system stability and transparency. The work in [156], [157] investigated wave variables to incorporate master and slave position errors, proposing joint position, velocity, and force signals and transmitted them as wave integrals to compensate for position tracking errors. However, they only considered constant unknown communication time delay. Recent studies have proposed WVA extensions to alleviate the challenge with varying time delays for haptic teleoperation services. Table 8 summarizes promising WVA based solutions for haptic teleoperation systems.

In [78], the authors proposed a WVA variation control design for tele-driving over time delayed communication networks, dealing with surface slippage under constant time delay in haptic-enabled tele-driving. They estimated real-time

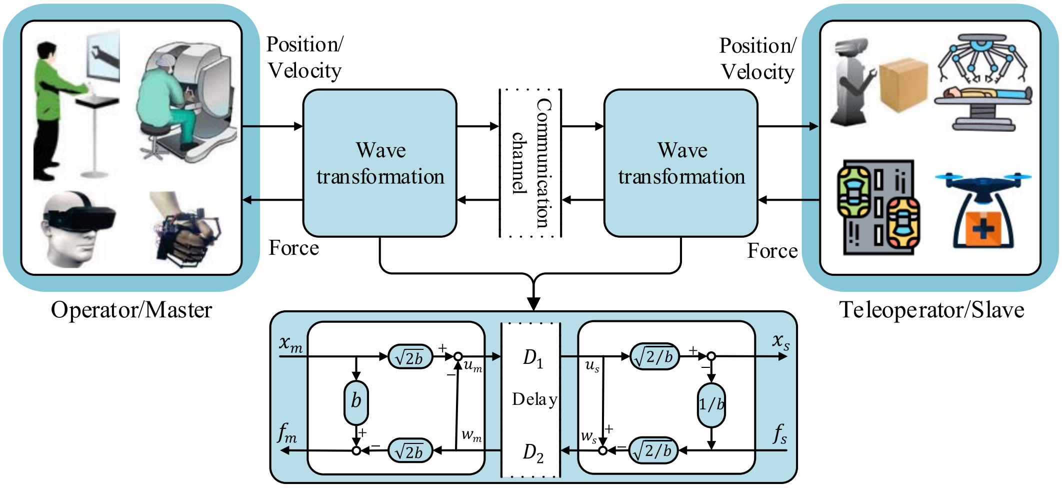

FIGURE 14. Wave variable transformations strategy for teleoperation systems to compensate communication delay under passivity framework (notations are defined in Table 3).

terrain parameters and improved control algorithm stability and transparency for autonomous vehicles over slippery terrain. The results show that the proposed scheme can compensate for the time delay and slave side environment termination non-passivity by employing wave transformation and guaranteeing conservative stability conditions to improve QoE. However, the authors ignored variable time delay, which is one of the critical QoS parameters. Control model performance and guaranteed stability was demonstrated using Llewellyn and passivity criterion.

The authors in [158] proposed a less conservative control design called wave variable compensation. Significant contributions for the proposed approach were improved tracking performance for both position/velocity and force reflection to advance telerobotic surgery. The proposed structure efficacy was analyzed experimentally and by simulation. The proposed wave variable compensation structure guaranteed the whole system passivity while maintaining the system's transparency. Transparency, also known as telepresence, directly impacts the QoE requirement. So, the analysis shows that WVA under time delay can achieve stable tracking performance while ensuring system QoE. However, the time delay value in the communication channel is set around 200 ms, which is very high compared to emerging telehaptic applications. The study in [159] applied linear control theory to optimize the WVA tuning parameter. However, the linearized model does not consider variable time delay. Subsequently, [160] proposed a WVA based wave predictor incorporating the Kalman filter and an energy regulator. The proposed method was applied on the master-side to predict slave side wave variables. The wave predictor compensated for communication variable time delay and improved system stability. A recent comparative study considered Smith predictors and WVAs under passivity framework for bilateral force feedback teleoperation systems [161].

The work [162], [163] extended WVAs by combining them with other strategies to optimize control design. Reference [162] proposed a control design for haptic-based bilateral tele-rehabilitation systems for the human lower limb, developing wave and phase-lead filters for the proposed control design to ensure patient side stability. The objective of the proposed phase-lead filter is to stable the tele-rehabilitation system in the presence of time delay and minimize the position error as well. For the experimentation, they considered a constant time delay of 20 ms to compensate for the stability effect. The authors in [163] incorporated Artificial Neural Networks (ANNs) with WVA to ensure stability under time-varying communication delay. Experimental results confirmed that the proposed hybrid control scheme improved tracking performance for both position and force feedback compared with the proportional-derivate controller. Several other WVA variations have been proposed under the passivity framework for bilateral teleoperation systems [164], [165], [166], and control schemes for multilateral teleoperation systems have also been discussed [167], [168], [169].

b: TIME-DOMAIN PASSIVITY APPROACH

The Time-Domain Passivity Approach (TDPA) is another effective option under the passivity framework to stabilize haptic bilateral teleoperation systems in the presence of unknown and varying time delays in communication channels [185]. As discussed in Section IV-B1, the passivity framework provides a mechanism way to understand nonlinear systems based on power flow and energy behavior. The TPDA advantage is that it does not need to convert power flow parameters into wave variables, and it is model-free, i.e., it does not need prior knowledge about environment dynamics and/or varied time delay effects. Reference [186] compared WVA and TDPA performance for force feedback bilateral teleoperation systems, where TDPA utilized Passivity Observer (PO) and Passivity Controller (PC) to guarantee teleoperation system input/output stability. PO monitors teleoperation energy flow each second, whereas PC dissipates extra energy to ensure passivity system and acts as a damper

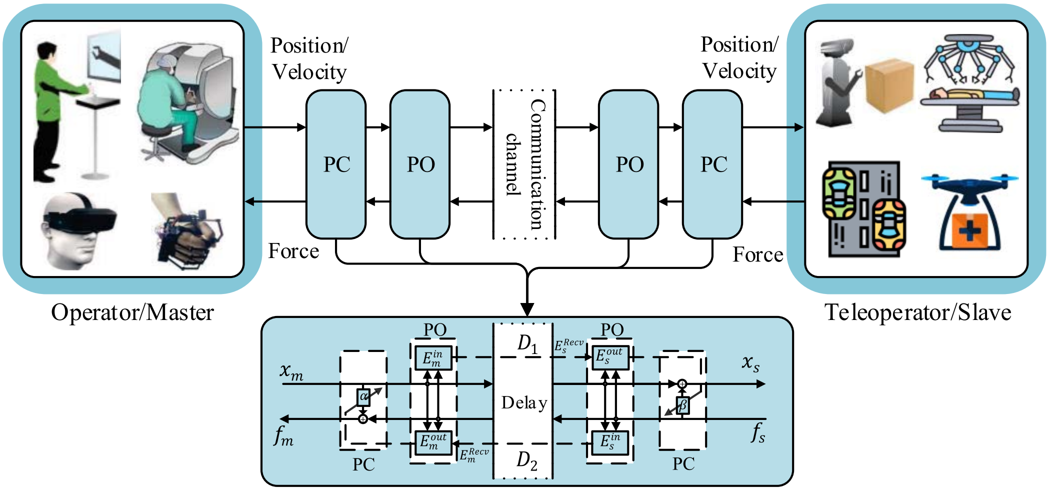

FIGURE 15. **Overview of the time-domain passivity approach for teleoperation systems to compensate varied time communication delay under passivity framework (notations are defined in Table 3).**

variable. Fig. 15 duplicates the TDPA for haptic bilateral teleoperation system over variable-time delay communication channels from [170]. The PC setting depends on controller design and can be used in series or parallel configuration. Adjustable damping elements (α and β) are used to dissipate extra energy and maintain system passivity.

Conventional proposed TDPA [185], [187] was limited to 1 DoF and faced tracking error challenges. These were extended to tackle varying-time delay challenges [188], [189], such as position tracking and synchronization error. However, although these solutions address various challenges under varying time delays with multi-DoF, transparency remains an open problem. The study in [171] proposed an NN based control design to examine power flow and address position and force tracking problems. The proposed TDPA improved position and force rendering under extensive and fast time-varying delay, and was subsequently compared against traditional PO, using the Lyapunov theorem to analyze system stability. The simulation results indicate the proposed passivity controller does not disturb the position and force tracking under the jitter effect. The proposed control algorithm is capable of handling external (human/environment) and internal parametric uncertainty and guarantees the stability of the system. Contrary to the stringent requirement of QoS and QoE for telehaptic systems, the time delay is set between 100 ms to 200 ms during experiments. A Modulated Time-Domain Passivity Controller (M-TDPC) was proposed [172] to exploit the operator's hand biomechanics to ensure passivity and enhance transparency for haptic-enabled bilateral rehabilitation systems. The modified four-channel Lawrence's control scheme was utilized under the passivity theorem to investigate system stability and force-feedback transparency [190].

Reference [173] employed TDPA for asymmetrical multi-DoF haptic-enabled teleoperation systems to find TDPA limitations and proposed solutions to tackle them. The proposed control design combined previous studies [191] and [192], where the PO was reset if there was no active energy output and force feedback was less than a defined threshold. Experimental results confirmed the proposed system promised stability if the teleoperation system had an impedance type master domain and admittance type slave domain. State-of-the-art TDPA was extended with multi-DoF under randomly varied time delay to address force fluctuation and position tracking error [170], called Cross-Dimensional Artifacts (CDAs). The authors argued their proposed projection-based control design could eradicate system artifacts and maintain a fair trade-off between stability and transparency in terms of QoE. CDA aims to achieve good QoE under QoS latency parameter value 100 ms.

In [174], the authors extended TDPA to address complex bimanual teleoperations, where energy flow is exchanged between two haptic-enabled telerobot arms. The authors evaluate the architecture in two real scenarios to experimentally prove the proposed TDPA extension effectiveness. The effect of delay and low control loop frequency on the system QoE in terms of stability and transparency was investigated. They simulate the system with RTT 50 ms in the network, and the results show that it can achieve good performance under constant delay. The system remained stable even if utilized with multilateral teleoperation systems. Several TDPA extensions for multilateral haptic teleoperation systems have been proposed recently [193], [194]. The traditional TDPA block diagram for multilateral teleoperation systems was converted into a network portrait with energy flow to understand system parameters [194], and an experiment was conducted with a trilateral teleoperation system to analyze stability.

2) ADAPTIVE CONTROL APPROACH

As discussed in Section IV-A and IV-B1, packet loss and communication delay disturb teleoperation system stability and transparency, and many methods have been proposed

TABLE 8. Comparison of the different control schemes.

Scope	Reference	Improved QoS/QoE						Stability Analysis			Application	Major Contribution
		Latency		Errors								
		Unknown	Variable	Position/Velocity	Force Feedback	Parametric Uncertainty	Model Jump Effect	Passivity Theorem	Lyapunov Theorem	Subjective Experiment		
WVA	Li *et al.* [78]	×	×	✓	✓	×	×	✓	×	×	Tele-driving	Improve control algorithm via real-time estimation of slippage-induced velocity error.
	Guo *et al.* [158]	×	✓	✓	✓	×	×	✓	×	×	Tele-driving	Two energy reservoirs based controller are constructed to bound the wave variables under the passivity framework.
	Kawai *et al.* [162]	×	✓	✓	×	×	×	×	✓	×	Tele-rehabilitation	Design the phase-lead filter to satisfy the patient side stability.
	D'Amore *et al.* [159]	×	×	✓	×	×	×	✓	×	×	Haptic teleoperation	Present a linear model to optimize the wave transformation.
	Yang *et al.* [163]	×	✓	✓	✓	×	×	×	✓	×	Haptic teleoperation	Focus on improving stability by combining NN models and WVA.
TDPA	Xu *et al.* [170]	×	✓	✓	✓	×	×	✓	×	×	Haptic teleoperation	Focus on eliminating force fluctuation and position tracking error to maintain system passivity.
	Sun *et al.* [171]	×	✓	✓	✓	×	×	×	✓	×	Haptic teleoperation	Improve the position and force tracking performance under fast varying delay.
	Atashzar *et al.* [172]	×	✓	✓	✓	×	×	✓	×	×	Tele-rehabilitation	Deal with non-passivity by delivering the user's hand passivity characteristics.
	Buongiorno *et al.* [173]	×	✓	✓	✓	×	×	✓	×	×	Tele-rehabilitation	Integrate energy and time threshold to reset PO with a focus to guarantee stability and transparency.
	Porcini *et al.* [174]	×	×	✓	✓	×	×	✓	×	×	Tele-rehabilitation	Investigate delay and low control loop frequency effect on the stability of the system.
Adaptive	Hashemzadeh *et al.* [175]	✓	✓	✓	×	✓	×	×	✓	×	Haptic teleoperation	Focus on synchronizing the environment states to ensure stability of the system.
	Forbrigger *et al.* [176]	×	✓	✓	✓	✓	×	×	✓	×	Surgical training	Deal to improve uncertain and delayed haptic output virtual environment.
	Na *et al.* [177]	×	✓	✓	✓	×	×	×	✓	×	Haptic teleoperation	Improve the tracking performance along with operator's hands' disturbance and sensors data compensation.
	Hu *et al.* [178]	X	✓	✓	✓	×	×	×	✓	×	Surgical training	Find the best tradeoff between stability and transparency by applying the proposed maximum force feedback controller.
Robust	Hao *et al.* [179]	×	✓	✓	✓	✓	×	×	✓	×	Tele-surgery	Integrate SMC with disturbance observer to tackle tracking error and stability issues.
	Pediredla *et al.* [180]	✓	✓	✓	✓	✓	×	×	✓	×	Haptic teleoperation	Present multimodal adaptive algorithm to deal tracking errors, nonlinearities, and environment uncertainties under variable time delay with a focus to ensure stability and transparency.
MMT	Guo *et al.* [181]	✓	✓	✓	✓	✓	✓	×	×	✓	Tele-palpation	Present a model-based design integration Kevin-Boltzmann model and self-perturbing recursive least squares algorithm to improve both force feedback and position/velocity tracking for tele-palpation application.
	Lia *et al.* [182]	×	✓	✓	✓	✓	✓	✓	×	×	Surgical applications	Propose a nonlinear MMT for surgical applications incorporating Hunt-Crossly, log linear and recursive least squares techniques to ensure stability and transparency.
	Song *et al.* [183]	✓	×	✓	✓	✓	✓	×	×	✓	Haptic teleoperation	Present a force-based updating model to reduce the effects of model jumping such as force disturbance.
	Yazdankhoo *et al.* [184]	×	✓	✓	✓	✓	✓	✓	×	×	Haptic teleoperation	Present a control design introducing fully decoupling between master and slave side during period of mismatch to ensure stability and high level of transparency.
	Beik *et al.* [51]	✓	✓	✓	✓	✓	✓	×	×	✓	Haptic teleoperation	Present a framework integrating dynamic movement primitives and RL technique to ensure stability in long-distance teleoperation with long communication delay

to tackle the challenges under the passivity framework. However, several model parameter uncertainties degrade teleoperation system stability and transparency in addition to network delays. These dynamic uncertainties arrive from master and slave domain complexities and nonlinearities. Traditional mathematical techniques are inefficient at dealing with these parametric uncertainties and communication delays, and hence several synchronization based approaches have been proposed to tackle these uncertainties. Synchronization-based techniques design parameter estimation algorithms to eliminate external parametric disturbances and uncertainties and synchronize local and remote environment parameters. Adaptive controllers for teleoperation systems are classified into four major research areas: estimate master and slave environments, communication delay compensation, disturbance rejection, and multiple function adaptive control. Detailed descriptions for the different teleoperation system adaptive controllers are available in [195].

Earlier studies on adaptive controllers proposed a state synchronizing adaptive controller for haptic-enabled teleoperation systems [175] designed to synchronize local and remote environment parameters under unknown and varied communication delays. A similar approach designed the controller based on feedback gain predictions [176] to address delayed output in an uncertain virtual environment.The proposed adaptive controller eliminated tracking error and maintained stability during interaction with the virtual environment. The authors investigate the sampling and delay effects induced by computation during interaction with a remote environment. The goal of the proposed is to provide the desired QoE to the human operator while ensuring the stability of the close loop in the presence of computational and sampling effects. Reference [177] proposed an impedance force controller to compensate for parametric disturbance and sensor noise and hence improve tracking performance, and [178] proposed predicting maximum output force for the system to maintain passivity of the system. The proposed controller limited extra forces to improve stability and provide maximum fidelity.

3) ROBUST CONTROL APPROACH

A control approach is robust if it addresses disturbance factors such as model uncertainties, frictional and external interaction forces, and parametric disturbance and ensures stability. The fundamental goal for robust control approaches is to tackle these disturbances, including unmodeled dynamics, and guarantee stability while maintaining remote task performance over distance communication. The robust control approach observes the worst communication network conditions that threaten system efficacy and degrade system transparency and stability. The difference between adaptive and robust controllers is that robust controllers have predefined bounds on model uncertainties, and internal and external disturbances, whereas adaptive controllers are not dependent on prior system dynamics knowledge. Many advanced controllers combine adaptive and robust controllers to provide system robustness, and many advanced robust control schemes have been utilized for haptic teleoperation systems, including, Sliding Mode Control (SMC), μ-synthesis, and H_∞. SMC moves system states on a well-defined sliding surface, and comprises two parts: the sliding surface design, and a control law that converges the signals.

An SMC incorporating Disturbance OBserver (SMC-DOB) was proposed for surgical teleoperation systems [179]. The DOB operates as feedforward and SMC as feedback controller. The DOB estimates disturbance and uncertainties, whereas SMC provides system robustness in the presence of these challenges. The proposed SMC-DOB performance was evaluated through simulation and experiment, confirming it tackles the chattering problem and significantly improved system tracking performance compared with traditional SMC. The authors in [180] proposed a multimodal adaptive robust control (MARC) algorithm for haptic teleoperated systems to enhance haptic feedback quality. The proposed SMC ensured system stability and provided high-fidelity transparency while handling varying time delay, position/velocity error, parametric uncertainty, external forces, and environment nonlinearities. An adaptive algorithm was employed to estimate environment parameters and was validated by simulation and experiment. The proposed MARC performance was compared with baseline models for MSE.

4) MODEL-MEDIATED TELEOPERATION

Network impairments, such as communication delay and packet loss, jeopardize teleoperation system stability and transparency, as discussed above. However, the aforementioned control designs retain system stability but sacrifice transparency [196]. Therefore, a Model-Mediated Teleoperation (MMT) approach was introduced to trade-off between stability and transparency in the presence of time-varying communication delay and haptic packet loss over the communication network, as shown in Fig. 16. The MMT scheme uses a model for the slave domain to estimate environment parameters and then sends these parameters to the local virtual model for the master domain rather than sending the force feedback directly to the master domain. The local virtual model at the master domain is updated in real-time whenever the slave environment changes. Force feedback is generated from the local virtual model and transmitted to the teleoperator at the master domain without delay. However, it is challenging to achieve modeling and defining the slave domain environment structure, real-time estimation, and updating parameters for the local virtual model simultaneously. One difficult aspect is to develop an accurate interaction and estimation model for the highly dynamic environment with communication delay.

Early MMT studies [197], [198] have been reviewed previously [199], including considering potential challenges and solutions, and exploring various MMT approach properties. However, they ignored critical haptic-driven aspects for applications over the Tactile Internet, nor did they effectively explore QoS and QoE provisioning to meet the Tactile Internet requirements. Therefore, the current paper discusses

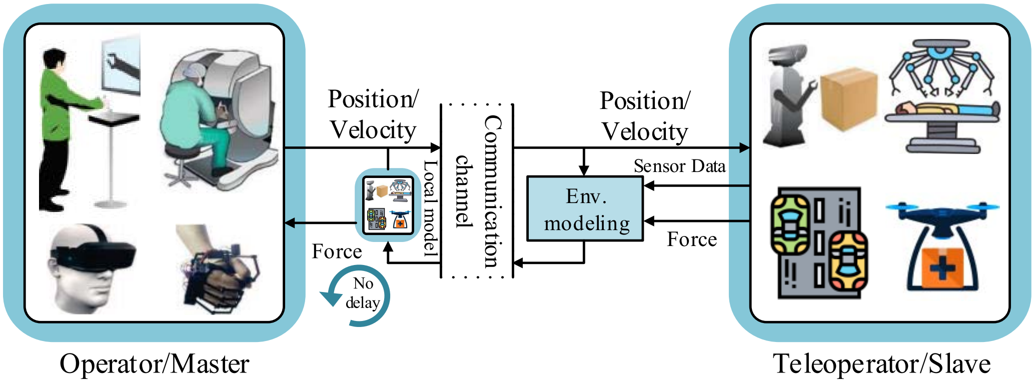

FIGURE 16. Block diagram of model-mediation scheme design (notations are defined in Table 3).

integrating various strategies to improve QoS and QoE for haptic-enabled smart applications for the Tactile Internet, specifically teleoperation systems.

Reference [181] proposed a model-based teleoperation design for robotic-assisted tele-palpation considering force feedback and position/velocity tracking error under arbitrary communication delay in a highly dynamic environment. They employed a self-perturbing recursive least squares algorithm to estimate environment parameters online and minimize communication delay, with a viscoelastic model to characterize soft tissue interaction. Simulation results confirmed the proposed scheme improved perception for haptic-enabled teleoperation systems, and QoE in terms stability and transparency compared with baseline. However, the constant time delay value is set at 500 ms, and for varying, it is around 400 – 600 ms.

The work in [182] proposed a nonlinear MMT for surgical applications based on a nonlinear Hunt-Crossly predictor log linearization method and recursive least squares. The authors considered QoS challenges, including communication delay, and bandwidth for haptic-enabled bilateral teleoperations, etc., focusing on providing guaranteed stability and transparency. Recursive least squares and linearization were applied for the slave-side to estimate remote environment parameters in real-time. Then Hunt-Crossly was employed on the master-side to predict force feedback. Performance metrics confirmed the proposed scheme's robustness in a highly dynamic and complex environment with time-varying delays.

In [183], the authors proposed a control design to minimize model jumping based on an adaptive impedance controller and novel model updating algorithm. The adaptive impedance controller was deployed on the slave-side to estimate physical environment parameters with the ability to adjust its behavior without state transition; and a force-based updating local controller was employed on the master-side to update stiffness. The authors focused on force-based rather than parameter-based updating, and the proposed force-based schemes aimed to provide force feedback from the master device with no delay. The proposed scheme was evaluated experimentally via a Geomagic Touch haptic device with 1 DoF and constant 5 s delay. Their results confirmed the proposed method could handle force disturbance and improve system QoE.

Similarly, the study in [184] proposed a model-based control design that decoupled master and slave during state transitions to ensure system stability and high transparency. The authors overcame model jumping effects causing a mismatch period, i.e., an interval when the master-side local model is not informed about the new environment parameters. Hence the local model can generate incorrect force feedback and ultimately destabilize the whole teleoperation system. They also fully decoupled master and slave when a new environment was encountered. Simulations on hard and soft environments confirmed the proposed approach improved system stability and transparency in the presence of large delays. They considered the one-way communication channel delay equivalent to 1 s.

The authors in [51] proposed an MMT design incorporating model-free Reinforcement Learning (RL) and dynamic movement primitives for grasping and manipulation through a haptic hand-arm exoskeleton system. Dynamic movement primitives estimate slave site model changes and informs the system to adjust model uncertainties. Finally, they proposed actor-critic, a model-free RL-based algorithm, to explore the feasible solution. Simulation results confirmed the proposed framework improved and performed and could adjust to a new environment under varying communication delays with high environment and model uncertainties.

Summary and Insights: Haptic-enabled bidirectional teleoperation systems are very delay sensitive, causing jitter and packet loss in the communication network, eventually desynchronizing haptic data stream between master and slave domain, and hence generating challenges with tracking errors, instability, and low transparency. This section reviewed proposed potential solutions from recent studies to tackle these challenges, as summarized in Table 8. Optimal control design can compensate for E2E delay and ensure QoE for the Tactile Internet services.

C. HYBRID APPROACHES

This section discusses joint haptic codec and control schemes to ensure stability and transparency, focusing on improving

QoS and maximizing QoE. Table 9 compares current methods to integrate haptic codecs and stability-ensuring control methods.

Reference [200] proposed a perception-based scheme for point cloud-based Model-Mediated Teleoperation (pcb-MMT), using three-dimensional sensors to capture point clouds for the object in a remote environment then estimating the environment parameters in real-time. The proposed pcbMMT strategy ensured teleoperation stability and transparency for dynamic and complex environments with low haptic packet rate and delayed communication channels. pcb-MMT utilized a PDb approach to reduce transmission data up to 90% with guaranteed QoE for teleoperation, while ensuring stability and transparency with communication delay up to approximately 1,000 ms.

Switching strategies can help explore optimal hybrid control schemes for teleoperation systems with different delay ranges [201]. The authors proposed a dynamic switching approach to exploit TDPA+PDb and MMT+PDb control schemes to improve human operator QoE under different communication delays. The proposed adaptive switching scheme considered three-dimensional trade-off between QoE, delay, and control methods, and validated the proposed method experimentally. A commercial haptic device (Phantom Omni) was employed as the master and created a virtual environment for the slave using the Chai3D library. Their results confirmed the proposed method effectiveness in terms of delay and PLR.

Incorporating a non-passive Input-to-State Stability (ISS) method and PDb haptic data reduction achieved the best QoS and QoE for tactile services [202]. The proposed hybrid approach jointly reduced packet rate and minimized constant communication delay effects. The authors experimentally evaluated the proposed scheme performance: focusing on verifying the PDb approach impacts; and comparing QoE for ISS+PDb and TDPA+PDb approaches.

To provide a feasible solution for position drifts while improving QoE under various network unreliability, such as delay, jitter, packet loss, [203] considered cross-traffic data, stability, and transparency problems. They proposed a hybrid solution coupling energy reflection-based TDPA [206] and PDb to trade-off between haptic packet rate and teleoperation quality. Their proposed time-triggered PDb approach with energy-based TDPA dramatically reduced packet rate from 1000 to 100 packet/second with 150 ms delay. Simulation results for the proposed scheme achieved high compression rate and QoE while maintaining system stability and transparency with minimum delay, jitter, and PLR.

The authors of [204] investigate potential ML utilization with MMT systems to forecast delayed feedback signals to the master domain and subsequently improve QoE. They utilized a gradient boosting decision tree algorithm to construct motion and force feedback prediction models. The model was trained on original position/velocity and force feedback data. The gradient boosting decision tree based MMT system aimed to maximize perceptual transparency with a low haptic packet rate. The proposed model was compared with Hunt-Crossly based MMT in terms of force feedback prediction.

Reference [205] proposed wave-based TDPA to overcome model or environment parameter uncertainties using WVA and hence improve force tracking and position error performance, termed as wave-based TDPA. They presented the extended prescribed performance control algorithm to improve synchronization performance for position/velocity and force for the master and slave. The proposed wave-based TDPA aimed to ensure communication network passivity in the presence of variable time delays.

Summary and Insights: This section investigated hybrid control design solutions to achieve QoE in teleoperations using the control model and haptic codec schemes to improve QoS for the Tactile Internet smart applications. Most current studies employed the PDb codec scheme with passivity and non-passivity based control design to maintain QoS and QoE for haptic data stream in teleoperations. Thus, TDPA and MMT were mainly employed with codec schemes and were influential among the existing control solution.

TABLE 9. Hybrid approaches (abbreviations are defined in Table 2).

Reference	Haptic Codec	Control Scheme				Improved QoS/QoE factor(s)	QoE Evaluation		Major Contribution
		WVA	TDPA	MMT	ISS		Objective	Subjective	
Xu *et al.* [200]	PDb	×	×	✓	×	delay, PLR	✓	×	Propose a point cloud model to estimate the environment properties (Physical geometry) to enable a stable teleoperations.
Xu *et al.* [201]	PDb	×	✓	✓	×	delay, PLR	✓	✓	Present an adaptive switching strategy to explore optimal hybrid scheme.
Xu *et al.* [202]	PDb	×	×	×	✓	delay, PLR	✓	✓	Introduce a controller based on combining ISS and PDb to maximizing QoS and user's QoE.
Xu *et al.* [203]	PDb	×	✓	×	×	delay, PLR	✓	✓	Propose a joint solution using power-based TDPA and PDb approach to improve stability of the teleopertion under timely varying QoS.
Dena *et al.* [204]	PDb + ML	×	×	✓	×	delay, MSE	✓	×	Introduce a MMT approach utilizing gradient boosting decision tree algorithm to provide the feedback signals without delay.
Sun *et al.* [205]	-	✓	✓	×	×	delay	✓	×	Present a wave-based TDPA considering prescribed performance control algorithm to guarantee passivity of the communication network.

D. INTELLIGENT PREDICTION TECHNIQUES

Previous sections explored and discussed codec schemes and control system designs to reduce packet size and packet rate while improving QoE under arbitrary network QoS. This section analyzes how ML-based models are trained on haptic data and deployed on the master or slave side to predict missing signals and compensate for communication delays. We discuss intelligent prediction solutions to overcome processing and propagation delays in the communication network, including AI based predictive solutions to address the speed of light limitations. The intelligent prediction approaches can be utilized with any of the previously defined control schemes. As we discussed in previous sections, haptic traffic of both local and remote sides is orchestrated in real-time, and with little delay, remote operations are performed ineffectively due to delays in crucial feedback. Therefore, a prediction-based model integrated with control schemes helps ensure stability, reliability, and high fidelity during haptic interaction while forecasting the missing/delayed signals. ML-based solutions for the Tactile Internet have attracted considerable research attention recently. Reference [207] proposed ML-based algorithms to intelligently allocate bandwidth to enhance latency performance, [208] proposed a federated RL-based algorithm for resource allocation to minimize network latency, and [209], [210] proposed prediction techniques to address transmission delay during haptic communication.

The study in [223] reviewed AI-enabled edge caching and computing solutions to ensure QoE and QoE requirements for mission-critical smart applications over 5G communication systems. They compared existing deep learning, deep RL, and federated RL-based algorithms for caching and computing. The authors in [224] discussed perception schemes, control designs, robotic learning techniques, and AI methods to ensure complex remote teleoperations. However, these studies ignored haptic aspects of smart applications. Therefore, we discuss these challenges considering haptic aspects with feasible solutions. Table 10 classifies existing proposed solutions into master, slave, and network side prediction algorithms. Haptic traffic comprises two haptic interaction parameter types: position/velocity and force.

- Master-side algorithms predict position/velocity to determine operator motion and enhance system transparency. However, this is somewhat more challenging than predicting slave environment parameters because human actions are unpredictable for some applications.
- Slave-side algorithms predict teleoperator feedback signals and provided them to the operator to compensate for delayed signals.
- Network side algorithms predict network impairments in advance, then adjust QoS parameters depending on the haptic-enabled teleoperation type. Fig. 7 summarizes recent network side studies, with further details available in [207], [208], [223] and Table 10 summarizes the master and slave side prediction algorithms.

The work in [211] proposed a predictive method to predict human motion aiming to maximize QoE for teleoperation systems, employing ANNs to estimate human hand position in real-time. Their proposed ANN based algorithm predicted not only human movement but also uncertainty in the prediction model. The algorithm collected initial data to train the model, and then predicted operator hand movements. The proposed approach does not require information regarding human intention before training the model, and performance metrics confirmed the proposed method could predict both trained and untrained human hand motion without delay, ensuring high transparency.

Similar to [211], the authors in [212] proposed an ANN based adaptive online predictive model to predict master-side movement and hence minimize network impairments (unknown and variable latency) and ensure QoE requirements for haptic-enabled teleoperation. In contrast with [211], the proposed predictive model considered both operator movement and network delay to enhance system transparency. The authors used an ANN with three neuron layers: the first layer takes master-side position and estimated time delay inputs; whereas the second layer approximates the output, and the final layer predicts future operator movement. The proposed algorithm was evaluated by simulation and experimentally. Performance metrics confirmed the presented algorithm effectively predicted master-side positions and delay.

Reference [213] proposed a human trajectory prediction algorithm to guide people in disaster areas and help visually impaired people avoid serious accidents. They utilized a haptic-enabled robot to interact with humans and human-robot interaction to realize behavioral patterns and collect multimodal haptic data for human trajectories. The haptic-enabled robot comprised a haptic device (Omega 7) and a camera to collect depth information for the human interaction. They used recurrent neural networks with double-layer gated recurrent unit to predict human future trajectory without visual signals. Experimental results confirmed the proposed algorithm improved human-robot interaction to guide people and enhance social intelligence.

The work in [214] proposed a positional data prediction algorithm to synchronize positions between both teleoperation haptic peers under different network impairments, including delay, jitter, and packet loss. They proposed a network-adaptive Trust Strategy Prediction (TSP) to predict haptic data in real-time and hence minimize haptic data stream desynchronization and improve operator QoE. The proposed TSP algorithm efficacy was measured experimentally for master and slave environments under different delay, jitter, and packet loss. They compared TSP under constant and variable delay $= 0 - 200$ ms and packet loss $= 10\% - 40\%$, verifying indicate the proposed TSP outperformed baseline in terms of delay and PLR. In [225] an intelligent communication framework has been proposed to consider the effects of prediction error on reliability in Tactile Internet services. The proposed framework consists of two major parts, prediction algorithm, and decision making algorithm. The former estimate the network condition and operator/teleoperator's behavior, while the later one utilizes the output of the first block to maximize the reward and take the possible best decision.

Reference [215] discussed a haptic-enabled bilateral teleoperation system for beating-heart surgery that requires a delay in milliseconds with PLR $\approx 10^{-7}$, focusing on combining an ANN based heart motion prediction model with impedance control design to compensate delayed heart positions and proving non-oscillator force feedback. Fig. 17 shows the impedance control approach and ultrasound image based heart motion prediction models for master and slave-side robots, respectively. The proposed teleoperation system included a human operator, beating heart, master, and slave robots. The human operator used the master robot to interact and control the slave-side robot for telesurgery. An ANN model was employed to predict beating heart motion utilizing ultrasound images and deploy it on a slave robot to compensate for time delay and synchronize heart and slave robot motion. The impedance control model on the master-side provided non-oscillatory force feedback to the human operator. The proposed system was evaluated experimentally and compared with two baseline models.

The study in [216], [217] recently proposed an AI-enabled approach to alleviating master-slave distance constraints. The authors extended [216], [217] Event based HAptic Feedback SAmple Forecast (EHASAF) to overcome E2E propagation delay [218]. The EHASAF framework comprises an ANN and RL module. The ANN classifies the control signals and makes decisions when haptic feedback is required. The RL unit ensures the proper haptic feedback signals are delivered to the master domain. The authors deployed an AI- embedded H2M server between master and slave to predict delayed haptic feedback and deliver it directly to the operator. A VR based teleoperation system was developed to examine the proposed EHASAF, and haptic feedback data was collected for further numerical analysis. They considered three cases to capture the control and feedback traffic patterns: grabbing virtual balls, cubes, and/or circular cubes. Collected control data and feedback signals were used to train distribution parameters to investigate E2E delay effects. The EHASAF framework was evaluated over time division multiplexed passive optical network-based fiber backhaul infrastructure, and EHASAF overcame delayed packet arrivals while facilitating H2M applications.

In [74], the authors proposed a fog-based framework for the Tactile Internet application called remote phobia therapy. The proposed fog-based architecture enabled the therapist to expose patient's feared objects, including spiders, snakes, cockroaches, scorpions, and mice, to cure their phobia via a shared virtual environment. VR environment was used to interact with each other and exchange haptic communication. However, they did not consider E2E delay latency requirements (50 ms) for tactile applications for teletherapy treatment. Moreover, QoS issues, such as packet loss and delay, which would degrade both therapist and patient QoE were not considered.

Reference [219] extended [74] to propose a cloud-based predictive scheme for haptic-enabled tele-VR phobia treatment. The proposed Edge Tactile Learner (ETL) aimed to provide QoS and QoE requirements between the therapist

TABLE 10. Intelligent predictive techniques (abbreviations are defined in Table 2).

	Reference	ML Methods	Improved QoS/QoE factor(s)	Application	Major Contribution
Master Side	Yazdankhoo *et al.* [211]	ANN	delay, MSE	Haptic teleoperation	Propose a predictive model to estimate the motion of the operator at master side to compensate the delayed network effects on teleoperation.
	Nikpour *et al.* [212]	ANN	delay, MSE	Haptic teleoperation	Present an adaptive online prediction algorithm to predict the master side postion/velocity and time delay to the network to ensure the high level of transparency of the teleoperation systems
	Moon *et al.* [213]	Recurrent NN	MSE	Human guide	Introduce an human trajectory prediction algorithm and deployed on haptic-enabled robot to guide the visually impaired peoples.
	Yap *et al.* [214]	-	delay, PLR	Haptic teleoperation	Present a network-adaptive algorithm to reduce the desynchronization between master and slave position data to compensate delay and packet loss effect.
	Cheng *et al.* [215]	ANN	delay, MSE	Beating-heart surgery	Propose an control model integrating with NN-based model to predict beating heart motion and deliver the non-oscillatory force feedback.
Slave Side	Mondal *et al.* [216]–[218]	ANN, RL	delay	VR teleoperation	Propose a two-pahse AI-enabled H2M server which utilized ANN and RL to forecast delayed haptic feedback signals with a focus to alleviating the master-slave distance limitation.
	Rasouli *et al.* [74], [219]	WKNN	delay, MSE	Phobia treatment	Propose a edge tactile learner based on weighted K-nearest neighbors to achieve the requirement of the specific tactile application, a tele-VR phobia treatment.
	Pérez-del-Pulgar *et al.* [220], [221]	GMM/GMR	MSE	Haptic teleoperation	Introduce a GMM-based predictive model that utilized GMR to reproduce the haptic feedback profiles to support telerobotic operator guidance.
	Boabang *et al.* [222]	HMM/ GMR	delay, PLR	Needle insertion	Present an HHM/GMR-based model to predicting force feedback for needle insertion during tele-surgery application.

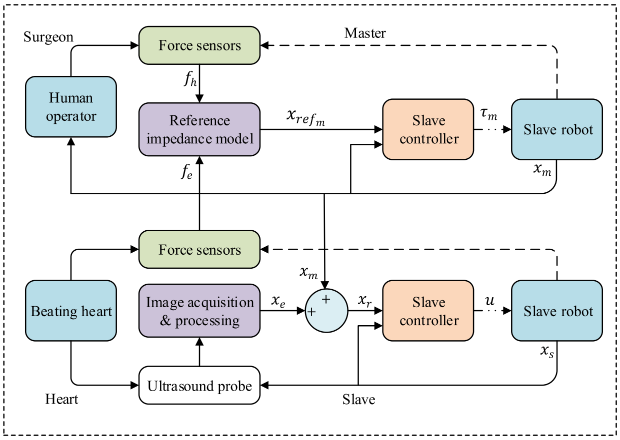

FIGURE 17. The telerobotic beating-heart surgery system. (adopted from [215] and notations are defined in Table 3).

and patient for haptic manipulation. The proposed framework included three components: therapist, cloud based network, and patient. The therapist and patient interacted each other through a cloud based 5G network infrastructure, exchanging bidirectional haptic information in addition to traditional traffic. Under the proposed framework, the therapist first touches the phobia object in his zone, and the corresponding feedback is transmitted to both therapist and patient. If feedback was not received within a defined timeout, the proposed ETL predicted the feedback and delivered it to the patient with a timeout. The authors utilized Weighted K-Nearest Neighbors (WKNN) to train the ETL and predict feedback for the selected phobia object. Performance results confirmed the proposed ETL predicted and provided feedback to the patient with a defined delay threshold = 50 ms.

The work in [220] proposed a predictive model using the Learning from Demonstration (LfD) concept to perform a peg-in-hole insertion experiment via telerobot. The authors adopted a Gaussian Mixture Model (GMM) to encode the force/torque profile and then used Gaussian Mixture Regression (GMR) to retrieve haptic feedback profiles online. The GMM/GMR model achieved good accuracy for the limited application but cannot be used for needle insertion during telesurgery. They also did not consider that predicting haptic feedback samples should reach the master operator before generating the next slave-side feedback. An extended version of this approach used GMM to haptically guide the operator for telemanipulation [221].

Subsequently [222] applied the Hidden Markov Model (HMM) rather than GMM to fit the force/torque profile along with other parameters, and hence proposed an HMM/ GMR based model. The GMR model predicts haptic feedback and delivers it to the surgeon during telesurgery to replace lost or delayed feedback. The HMM/GMR model considering the stringent delay limitation and prediction accuracy. They used the publicly available needle interaction dataset for simulation analysis [230]. The dataset comprises 39 needle insertion forces, recorded during needle insertion and retraction into the liver. The authors showed the proposed model could

TABLE 11. Haptic databases.

Database	Type	Samples	Capturing tool	References
Penn haptic texture toolkit	Various	100	6-DoF custom handheld device	[226]
LMT haptic texture database	Surface material	184	Haptic stylus	[144], [227]
HapTex	Fabric	120	Custom device (TexRecorder)	[228]
-	Various	100	Force sensors phantom premium device	[229]
Needle insertion	Insertion and retraction forces	39	Trocar needle	[230]
-	Various	100	Tactile sensor	[231]
Technical university of munich database	Surface material	280	Custom device	[143]
Open access haptic database	various	18	Tactile skin sensor	[232]
Open access haptic database	Thermal sensing	69	Thermal sensor	[233]
Open access haptic database	Thermal sensing	69	Thermal sensor	[233]
Haptic texture database	Surface texture	43	Geomagic device with custom stylus tip	[234]
Universal haptic library	Surface texture	84	Subjective selection	[234]

TABLE 12. Testbeds for Tactile Internet.

Testbed	Standard	Non-Standard	Major Contribution
NFV-Enabled 5G Tactile Internet platform [56]	×	✓	Present a NFV-enabled platform to support 5G Tactile Internet delay-sensitive applications.
TCPSbed [235]	×	✓	Introduce a platplorm of tactile CPSs employing ns-3 for network simulations.
Adjustable instrumented multisensory stimuli (AIMS) [236]	×	✓	Present a haptic testbed system to analysis and comparing the different cutaneous haptic cues.
Haptic system testbed [15]	×	✓	Propose a platform for haptic communication considering centralized interface to provide latency assistance.
Tactile Internet extensible testbed (TIXT) [237]	✓	×	Propose an extensible testbed for Tactile Internet communication following the lines of IEEE P1918.1 Tactile Internet reference architecture.
Otto-von-guericke university-haptic communication (OVGU-HC) [238]	✓	×	Present a data-driven experiment design for haptic-driven applications with a focus on communication flow.

predict missing or delayed force feedback signals in a shorter time than the GMM/GMR-based model.

Summary and Insights: This subsection discussed intelligent prediction techniques and summarized them in Table 10. To overcome challenges due to lost/delayed control and/or feedback signals during remote manipulation between the master and slave over the communication channel, exiting solutions were categorized into three classes: the master, network, and slave-side. Fig. 7 shows studies with key contributions on the network side, and Table 10 shows the remaining systems. Thus, although AI assisted predictive strategies can help to improve master-slave distance and processing limitations, predicting human operator position/velocity at the master-side is more challenging than predicting haptic feedback signals. Considerable research has become focused in this direction to meet the Tactile Internet services requirements.

V. OPEN RESEARCH CHALLENGES AND FUTURE DIRECTIONS

This section presents open research challenges and potential future research directions to realize the Tactile Internet stringent requirements. Despite significant existing literature on surveyed schemes, including haptic codecs, control, and intelligent prediction schemes, certain aspects of these schemes are still facing challenges. As discussed in Section IV-A, most existing research focused on kinesthetic characteristics for haptic data, with little work dedicated to haptic tactile aspects. Similarly, haptic bilateral control systems remain an open issue and require further investigation to identify different feasible trade-off solutions for energy-latency, latency-synchronization, and stability-transparency. The QoS and QoE provisions for haptic-driven and other delay sensitive Tactile Internet services require optimal intelligent codecs, adaptive prediction, and control design solutions to compensate for network impairments. Fig. 18 summarizes open research issues and desirable future study directions and is discussed as follows:

a) *Automatic data rate mechanism*: Challenges for tactile codec with multiple interaction points in a wireless network with latency limitations have not been properly explored [22]. Advance ML-based models can provide low data rate vibrotactile codecs while maintaining required QoS, and QoE [239]. Specifically, RL techniques should be explored to adjust the packet rate mechanism for rate-sensitive network conditions.

b) *Cross-model approach*: Low-delay haptic coding schemes are envisioned to minimize packet rate and improving QoS without degrading perceptual quality. However, it is very challenging to deal with both aspects (kinesthetic/ tactile) of haptic simultaneously, which requires investigating cross-modal approaches [240], [241].

c) *Universal benchmark databases and standard evaluation metrics*: Most proposed haptic coding schemes were evaluated on publicly available databases or proprietary collected data traces, with relatively simple HQA metrics to measure reconstructed signal quality, and no standard testbed. It is vital to define standard HQAs to measure perceived signal quality and develop testbed and standard databases for complex environments, similar to [242]. Tables 5, 11, and 12 show existing available HQAs, databases, and testbeds, respectively, in the research community, that can be used to investigate and recommend reasonable solutions, including academia and industries.

d) *Generic control model*: Many control methods have been proposed in the exiting haptic teleoperation studies to ensure stability and transparency tradeoff. However, most achieve acceptable system stability by dropping performance in terms of transparency and tracking precision. The selection of a suitable control scheme for delay sensitive haptic teleoperation systems depend on network conditions (delay, packet loss); environment complexity or dynamics (model uncertainties), and understanding application aspects. There is a strong desire for a generic model to capture the dependencies highlighted above, which will also help understand control performance and selection of the proper control method [243]. The generic performance model can configure network parameters to assist the selected control method.

e) *Intelligent state prediction model*: One significant issue for bilateral teleoperation systems is synchronization or tracking performance error while considering variable time delay. Potential solutions need further evaluation and development, such as state synchronization schemes [244], wave filter models [245], and AI-enabled state predictive models [246].

f) *Online learning capabilities in MMT*: Several MMT approaches have been proposed to ensure control system stability and transparency. However, this approach has several critical challenges, including updating model parameters as rapid changes occur in remote environments, and removing model jumping effects. MMT cannot achieve good results in complex and unknown environments due to shortcomings in exiting online parameter estimation models. The current best ML-based online estimation algorithms include [214], [247] and the digital twins concept [248] can help to optimize MMT schemes.

g) *Adaptive switching strategies*: Many hybrid approaches integrating haptic data reduction and control schemes have been proposed to improve QoS and maximize QoE while ensuring system stability. Few, if any, studies have reported hybrid approaches and they were not well-explored. There is also potentially fruitful future research on designing switching strategies to adapt haptic codecs and control schemes depending on network details and environmental dynamicity [201], [205], [249].

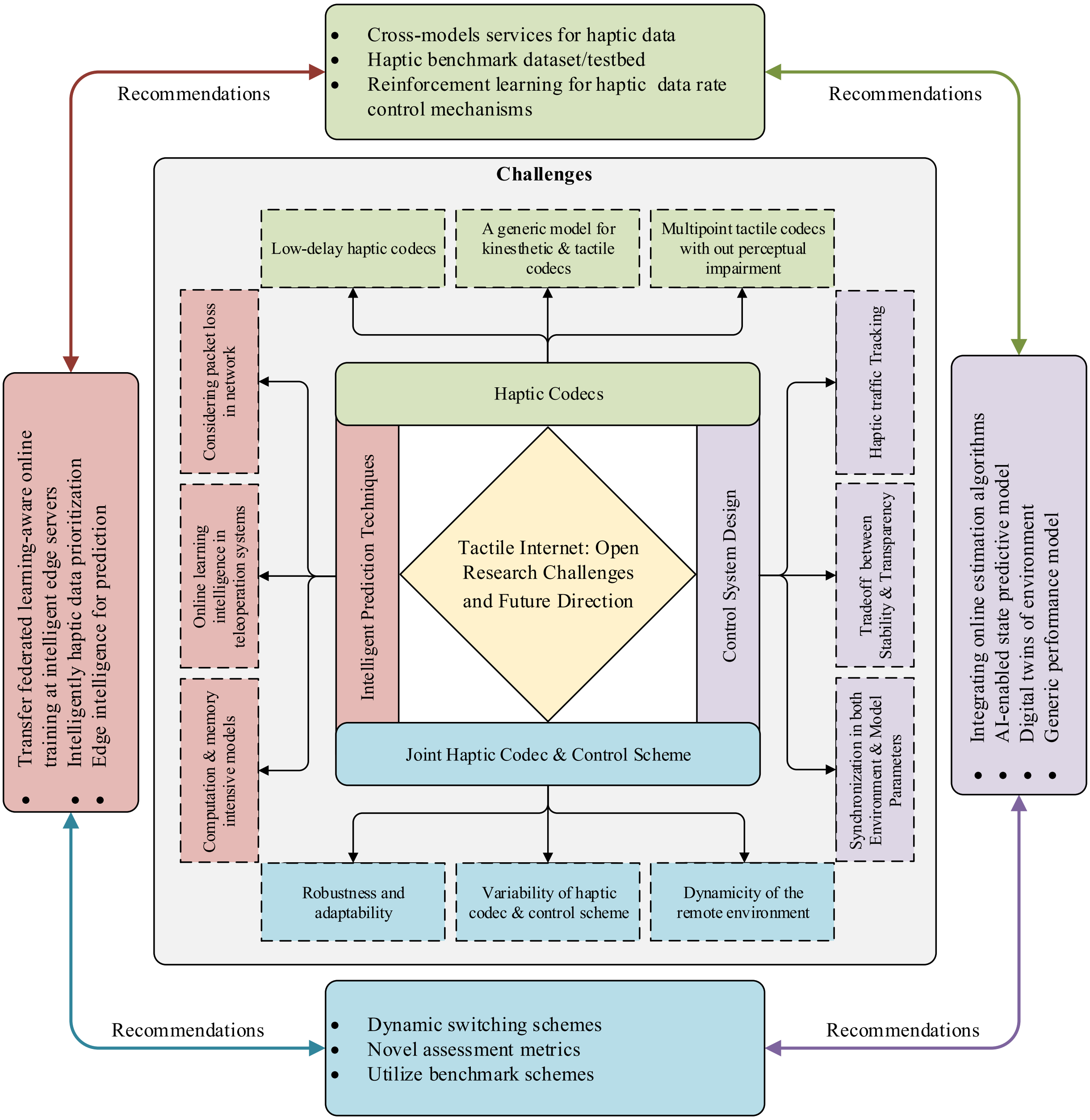

FIGURE 18. Research challenges and future directions.

h) *RL for prediction accuracy*: Several AI assisted prediction models have been proposed to predict haptic data, including control commands and haptic feedback in real-time and compensate for packet loss. However, the key challenge is maintaining prediction accuracy in teleoperations over unknown and time-varying delay communication channels. Online RL-based models should be explored to improve prediction accuracy [51], [218].

i) *Edge intelligence for haptic traffic prediction*: Several AI embedded fog/edge and cloudlets computing paradigms have been proposed to support the Tactile Internet services. Integrating AI with edge paradigms is a potential solution for predicting haptic traffic in real-time. However, these models are computation and memory intensive, hence there is strong need to explore lightweight intelligent models, such as federated learning-aware approaches [39], for edge intelligence [250], [251].

j) *Error resilience algorithm for prediction error*: Although prediction algorithms are designed to compensate for delay and packet losses, prediction errors occur due to network fluctuations in real-time. The Error Resilience Algorithm (ERA) is an efficient solution to compensate for prediction errors during haptic traffic transmission in the teleoperation under network fluctuations. Conventional ERA for haptic communication applies linear prediction methods, such as zero-order linear prediction and first-order linear prediction. Reference [252] proposed using artifacts that occur for perceptual-based approaches. Haptic traffic is not simply linear data, hence it remains challenging to enhance ERA performance and ensure algorithms make the best predictions to realize haptic-driven services. Few relevant studies have been reported [118], [253], hence this is a clear area for future study.

k) *Integration/Fusion of prediction and control schemes*: Prediction-based approaches have also been proposed to reduce communication traffic for the haptic-enabled control systems. Integrating prediction-based haptic (control/feedback) traffic reduction model with control system designs [254] can potentially improve haptic data transmission within limited bandwidth without degrading QoE.

VI. CONCLUSION

The Tactile Internet is an essential technology, providing revolutions in every field of life. It not only provides innovation in communication technology but also improves the user experience during interaction with the object (physical/virtual) at remote locations. Major challenges, including ultra-low latency, ultra-high reliability, high availability, and ultra-security, must be addressed to realize the Tactile Internet services. However, stringent QoS and QoE requirements become more critical for mission-critical or delay-sensitive Tactile Internet applications. This research area is still in its initial phases. Therefore, we reviewed QoS and QoE provisioning methods, including haptic codecs, haptic control designs, hybrid approaches, and intelligent prediction techniques. We investigated the various challenges and discussed strengths and weaknesses for various feasible approaches to ensure the Tactile Internet QoS and QoE requirements for applications. We categorized existing solutions into different classes and enlisted comparative analysis with a focus to guarantee system stability and transparency under varying-time delay and packet loss. Finally, we summarized the issues and presented insights for each section as open research challenges and potential future study directions.

REFERENCES

[1] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. Soong, and J. C. Zhang, "What will 5g be?" *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.

[2] M. Matthaiou, O. Yurduseven, H. Q. Ngo, D. Morales-Jimenez, S. L. Cotton, and V. F. Fusco, "The road to 6G: Ten physical layer challenges for communications engineers," *IEEE Commun. Mag.*, vol. 59, no. 1, pp. 64–69, Jan. 2021.

[3] W. Jiang, B. Han, M. A. Habibi, and H. D. Schotten, "The road towards 6G: A comprehensive survey," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 334–366, 2021.

[4] L. Babun, K. Denney, Z. B. Celik, P. McDaniel, and A. S. Uluagac, "A survey on IoT platforms: Communication, security, and privacy perspectives," *Comput. Netw.*, vol. 192, Jun. 2021, Art. no. 108040.

[5] G. P. Fettweis, "The tactile internet: Applications and challenges," *IEEE Veh. Technol. Mag.*, vol. 9, no. 1, pp. 64–70, Mar. 2014.

[6] G. Fettweis, H. Boche, T. Wiegand, E. Zielinski, H. Schotten, P. Merz, S. Hirche, A. Festag, W. Häffner, M. Meyer, and E. Steinbach, "The tactile internet-ITU-T technology watch report," Int. Telecommun. Union, Geneva, Switzerland, White Paper, 2014.

[7] *Study on Scenarios and Requirements for Next Generation Access Technologies*, document 3GPP TR 38.913 v15.0.0, 2018.

[8] B. Devlin, L. Borg, J. F. Snow, D. Schnuelle, S. Llamb, J. Watts, W. C. Miller, B. Long, B. Redmann, D. Bullock, P. Warren, T. Yamazaki, F. Walls, T. Kernen, L. Whitcomb, J. Footen, P. Gardiner, C. Witham, and F. Schleich, "Reports from the SMPTE technology committees," *SMPTE Motion Imag. J.*, vol. 127, no. 8, pp. 16–28, 2018.

[9] *ETSI IP6 Industrial Specification Group (ISG)*, Standard DGR/IPE-004, Work Item, 2022.

[10] O. Holland, E. Steinbach, R. V. Prasad, Q. Liu, Z. Dawy, A. Aijaz, N. Pappas, K. Chandra, V. S. Rao, S. Oteafy, and M. Eid, "The IEEE 1918.1 'tactile internet' standards working group and its standards," *Proc. IEEE*, vol. 107, no. 2, pp. 256–279, Feb. 2019.

[11] *Minimum Requirements Related to Technical Performance for IMT-2020 Radio Interface(s)*, document ITU-R M.IMT-2020, 2017.

[12] M. Maier, M. Chowdhury, B. P. Rimal, and D. P. Van, "The tactile internet: Vision, recent progress, and open challenges," *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 138–145, May 2016.

[13] A. Aijaz, M. Dohler, A. H. Aghvami, V. Friderikos, and M. Frodigh, "Realizing the tactile internet: Haptic communications over next generation 5G cellular networks," *IEEE Wireless Commun.*, vol. 24, no. 2, pp. 82–89, Oct. 2016.

[14] Z. S. Bojkovic, B. M. Bakmaz, and M. R. Bakmaz, "Vision and enabling technologies of tactile internet realization," in *Proc. 13th Int. Conf. Adv. Technol., Syst. Services Telecommun. (TELSIKS)*, Oct. 2017, pp. 113–118.

[15] D. Van Den Berg, R. Glans, D. De Koning, F. A. Kuipers, J. Lugtenburg, K. Polachan, P. T. Venkata, C. Singh, B. Turkovic, and B. Van Wijk, "Challenges in haptic communications over the tactile internet," *IEEE Access*, vol. 5, pp. 23502–23518, 2017.

[16] K. Antonakoglou, X. Xu, E. Steinbach, T. Mahmoodi, and M. Dohler, "Toward haptic communications over the 5G tactile internet," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 4, pp. 3034–3059, 4th Quart., 2018.

[17] A. Aijaz and M. Sooriyabandara, "The tactile internet for industries: A review," *Proc. IEEE*, vol. 107, no. 2, pp. 414–435, Nov. 2018.

[18] A. A. Ateya, M. Khayyat, A. Muthanna, and A. Koucheryavy, "Toward tactile internet," in *Proc. 11th Int. Congr. Ultra Modern Telecommun. Control Syst. Workshops (ICUMT)*, Oct. 2019, pp. 1–7.

[19] S. Aggarwal and N. Kumar, "Fog computing for 5G-enabled tactile internet: Research issues, challenges, and future research directions," *Mobile Netw. Appl.*, vol. 24, pp. 1–28, Nov. 2019.

[20] R. Gupta, S. Tanwar, S. Tyagi, and N. Kumar, "Tactile internet and its applications in 5G era: A comprehensive review," *Int. J. Commun. Syst.*, vol. 32, no. 14, Sep. 2019, Art. no. e3981.

[21] H. Yu, M. K. Afzal, Y. B. Zikria, A. Rachedi, and F. H. P. Fitzek, "Tactile internet: Technologies, test platforms, trials, and applications," *Future Gener. Comput. Syst.*, vol. 106, pp. 685–688, May 2020.

[22] S. K. Sharma, I. Woungang, A. Anpalagan, and S. Chatzinotas, "Toward tactile internet in beyond 5G era: Recent advances, current issues, and future directions," *IEEE Access*, vol. 8, pp. 56948–56991, 2020.

[23] C. She, C. Sun, Z. Gu, Y. Li, C. Yang, H. V. Poor, and B. Vucetic, "A tutorial on ultrareliable and low-latency communications in 6G: Integrating domain knowledge into deep learning," *Proc. IEEE*, vol. 109, no. 3, pp. 204–246, Mar. 2021.

[24] N. Promwongsa, A. Ebrahimzadeh, D. Naboulsi, S. Kianpisheh, F. Belqasmi, R. Glitho, N. Crespi, and O. Alfandi, "A comprehensive survey of the tactile internet: State of the art and research directions," 2020, *arXiv:2009.12164*.

[25] M. Simsek, A. Aijaz, M. Dohler, J. Sachs, and G. Fettweis, "5G-enabled tactile internet," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 3, pp. 460–473, Feb. 2016.

[26] A. Aijaz, "Towards 5G-enabled tactile internet: Radio resource allocation for haptic communications," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Apr. 2016, pp. 145–150.

[27] A. Hodaei and S. Babaie, "A survey on traffic management in software-defined networks: Challenges, effective approaches, and potential measures," *Wireless Pers. Commun.*, vol. 118, no. 2, pp. 1–28, May 2021.

[28] B. Yi, X. Wang, S. K. Das, K. Li, and M. Huang, "A comprehensive survey of network function virtualization," *Comput. Netw.*, vol. 133, pp. 212–262, Mar. 2018.

[29] Y. Mao, C. You, J. Zhang, K. Huang, and K. B. Letaief, "A survey on mobile edge computing: The communication perspective," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2322–2358, Dec. 2017.

[30] I. Parvez, A. Rahmati, I. Guvenc, A. I. Sarwat, and H. Dai, "A survey on low latency towards 5G: RAN, core network and caching solutions," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 4, pp. 3098–3130, 4th Quart. 2018.

[31] D. Kreutz, F. M. V. Ramos, P. E. Verissimo, and C. E. Rothenberg, "Software-defined networking: A comprehensive survey," *Proc. IEEE*, vol. 103, no. 1, pp. 14–76, Jan. 2014.

[32] H. Adhami, M. Al Ja'afreh, and A. El Saddik, "Can we deploy tactile internet applications over Wi-Fi, 3G and WiMAX: A comparative study based on riverbed modeler," in *Proc. IEEE Int. Symp. Haptic, Audio Vis. Environ. Games (HAVE)*, Oct. 2019, pp. 1–6.

[33] D. Szabo, A. Gulyas, F. H. Fitzek, and D. E. Lucani, "Towards the tactile internet: Decreasing communication latency with network coding and software defined networking," in *Proc. Eur. Wireless, 21st Eur. Wireless Conf.*, May 2015, pp. 1–6.

[34] E. Steinbach, S. Hirche, M. Ernst, F. Brandi, R. Chaudhari, J. Kammerl, and I. Vittorias, "Haptic communications," *Proc. IEEE*, vol. 100, no. 4, pp. 937–956, Apr. 2012.

[35] A. Masaracchia, Y. Li, K. K. Nguyen, C. Yin, S. R. Khosravirad, D. B. D. Costa, and T. Q. Duong, "UAV-enabled ultra-reliable low-latency communications for 6G: A comprehensive survey," *IEEE Access*, vol. 9, pp. 137338–137352, 2021.

[36] M. Sarac, M. Solazzi, and A. Frisoli, "Design requirements of generic hand exoskeletons and survey of hand exoskeletons for rehabilitation, assistive, or haptic use," *IEEE Trans. Haptics*, vol. 12, no. 4, pp. 400–413, Oct./Dec. 2019.

[37] A. Costes, F. Danieau, F. Argelaguet, P. Guillotel, and A. Lecuyer, "Towards haptic images: A survey on touchscreen-based surface haptics," *IEEE Trans. Haptics*, vol. 13, no. 3, pp. 530–541, Jul. 2020.

[38] G. S. Giri, Y. Maddahi, and K. Zareinia, "An application-based review of haptics technology," *Robotics*, vol. 10, no. 1, p. 29, Feb. 2021.

[39] M. Mukherjee, M. Guo, J. Lloret, and Q. Zhang, "Leveraging intelligent computation offloading with fog/edge computing for tactile internet: Advantages and limitations," *IEEE Netw.*, vol. 34, no. 5, pp. 322–329, Sep. 2020.

[40] S. Mehrdad, F. Liu, M. T. Pham, A. Lelevé, and S. F. Atashzar, "Review of advanced medical telerobots," *Appl. Sci.*, vol. 11, no. 1, p. 209, Dec. 2021.

[41] I. de la Torre Díez, S. G. Alonso, S. Hamrioui, M. López-Coronado, and E. M. Cruz, "Systematic review about QoS and QoE in telemedicine and eHealth services and applications," *J. Med. Syst.*, vol. 42, no. 10, pp. 1–10, Oct. 2018.

[42] D. Sun, W. Li, X. Yao, H. Liu, J. Chai, K. Xie, L. Zhu, and L. Feng, "Research on IoT architecture and application scheme for smart grid," in *Proc. 9th Int. Conf. Comput. Eng. Netw.* Changsha, China: Springer, Feb. 2021, pp. 921–928.

[43] Y. Issaoui, A. Khiat, A. Bahnasse, and H. Ouajji, "Toward smart logistics: Engineering insights and emerging trends," *Arch. Comput. Methods Eng.*, vol. 28, no. 4, pp. 1–28, 2020.

[44] Y. Liu, M. Peng, G. Shou, Y. Chen, and S. Chen, "Toward edge intelligence: Multiaccess edge computing for 5G and Internet of Things," *IEEE Internet Things J.*, vol. 7, no. 8, pp. 6722–6747, Aug. 2020.

[45] Y. Song, F. R. Yu, L. Zhou, X. Yang, and Z. He, "Applications of the Internet of Things (IoT) in smart logistics: A comprehensive survey," *IEEE Internet Things J.*, vol. 8, no. 6, pp. 4250–4274, Oct. 2020.

[46] P. Parekh, S. Patel, N. Patel, and M. Shah, "Systematic review and meta-analysis of augmented reality in medicine, retail, and games," *Vis. Comput. Ind., Biomed., Art*, vol. 3, no. 1, pp. 1–20, Dec. 2020.

[47] Y. A. Qadri, A. Nauman, Y. B. Zikria, A. V. Vasilakos, and S. W. Kim, "The future of healthcare Internet of Things: A survey of emerging technologies," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 2, pp. 1121–1167, 2nd Quart., 2020.

[48] H.-N. Dai, M. Imran, and N. Haider, "Blockchain-enabled internet of medical things to combat COVID-19," *IEEE Internet Things Mag.*, vol. 3, no. 3, pp. 52–57, Sep. 2020.

[49] S. Sedaghat and A. H. Jahangir, "RT-TelSurg: Real time telesurgery using SDN, fog, and cloud as infrastructures," *IEEE Access*, vol. 9, pp. 52238–52251, 2021.

[50] S. Handelzalts, G. Ballardini, C. Avraham, M. Pagano, M. Casadio, and I. Nisky, "Integrating tactile feedback technologies into home-based telerehabilitation: Opportunities and challenges in light of COVID-19 pandemic," *Frontiers Neurorobotics*, vol. 15, p. 4, Feb. 2021.

[51] H. Beik-Mohammadi, M. Kerzel, B. Pleintinger, T. Hulin, P. Reisich, A. Schmidt, A. Pereira, S. Wermter, and N. Y. Lii, "Model mediated teleoperation with a hand-arm exoskeleton in long time delays using reinforcement learning," in *Proc. 29th IEEE Int. Conf. Robot Hum. Interact. Commun. (RO-MAN)*, Aug. 2020, pp. 713–720.

[52] A. M. Borujeni, M. Fathy, and N. Mozayani, "Developing and evaluating a real time and energy efficient architecture for an Internet of Health Things," in *Proc. 4th Int. Conf. Smart City, Internet Things Appl. (SCIOT)*, Sep. 2020, pp. 106–111.

[53] T. Yang, D. Xie, Z. Li, and H. Zhu, "Recent advances in wearable tactile sensors: Materials, sensing mechanisms, and device performance," *Mater. Sci. Eng. R, Rep.*, vol. 115, pp. 1–37, May 2017.

[54] X. Jiang, R. Chen, and H. Zhu, "Recent progress in wearable tactile sensors combined with algorithms based on machine learning and signal processing," *APL Mater.*, vol. 9, no. 3, Mar. 2021, Art. no. 030906.

[55] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo, "Wearable haptic systems for the fingertip and the hand: Taxonomy, review, and perspectives," *IEEE Trans. Haptics*, vol. 10, no. 4, pp. 580–600, Oct./Dec. 2017.

[56] P.-V. Mekikis, K. Ramantas, A. Antonopoulos, E. Kartsakli, L. Sanabria-Russo, J. Serra, D. Pubill, and C. Verikoukis, "NFV-enabled experimental platform for 5G tactile internet support in industrial environments," *IEEE Trans. Ind. Informat.*, vol. 16, no. 3, pp. 1895–1903, May 2019.

[57] Ó. Blanco-Novoa, T. M. Fernández-Caramés, P. Fraga-Lamas, and M. A. Vilar-Montesinos, "A practical evaluation of commercial industrial augmented reality systems in an Industry 4.0 shipyard," *IEEE Access*, vol. 6, pp. 8201–8218, 2018.

[58] W. P. Neumann, S. Winkelhaus, E. H. Grosse, and C. H. Glock, "Industry 4.0 and the human factor —A systems framework and analysis methodology for successful development," *Int. J. Prod. Econ.*, vol. 233, Mar. 2021, Art. no. 107992.

[59] P. Schulz, M. Matthe, H. Klessig, M. Simsek, G. Fettweis, J. Ansari, S. A. Ashraf, B. Almeroth, J. Voigt, I. Riedel, and A. Puschmann, "Latency critical IoT applications in 5G: Perspective on the design of radio interface and network architecture," *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 70–78, Feb. 2017.

[60] B. Natesha and R. M. R. Guddeti, "Fog-based intelligent machine malfunction monitoring system for Industry 4.0," *IEEE Trans. Ind. Informat.*, vol. 17, no. 12, pp. 7923-7932, Feb. 2021.

[61] Y. A. Shim, K. Park, S. Lee, J. Son, T. Woo, and G. Lee, "FS-Pad: Video game interactions using force feedback gamepad," in *Proc. 33rd Annu. ACM Symp. User Interface Softw. Technol.*, 2020, pp. 938–950.

[62] D. Wang, K. Ohnishi, and W. Xu, "Multimodal haptic display for virtual reality: A survey," *IEEE Trans. Ind. Electron.*, vol. 67, no. 1, pp. 610–623, Jun. 2019.

[63] K. Murphy and M. Darrah, "Haptics-based apps for middle school students with visual impairments," *IEEE Trans. Haptics*, vol. 8, no. 3, pp. 318–326, Jul. 2015.

[64] G. Baud-Bovy and N. Balzarotti, "Using force-feedback devices in educational settings: A short review," in *Proc. 1st ACM SIGCHI Int. Workshop Multimodal Interact. Educ.*, Nov. 2017, pp. 14–21.

[65] Y. Lin, X. Wang, F. Wu, X. Chen, C. Wang, and G. Shen, "Development and validation of a surgical training simulator with haptic feedback for learning bone-sawing skill," *J. Biomed. Informat.*, vol. 48, pp. 122–129, Apr. 2014.

[66] C. G. Corrêa, F. L. S. Nunes, E. Ranzini, R. Nakamura, and R. Tori, "Haptic interaction for needle insertion training in medical applications: The state-of-the-art," *Med. Eng. Phys.*, vol. 63, pp. 6–25, Jan. 2019.

[67] F. Laamarti, F. Arafsha, B. Hafidh, and A. El Saddik, "Automated athlete haptic training system for soccer sprinting," in *Proc. IEEE Conf. Multimedia Inf. Process. Retr. (MIPR)*, Mar. 2019, pp. 303–309.

[68] T. Everson, M. Joordens, H. Forbes, and B. Horan, "Virtual reality and haptic cardiopulmonary resuscitation training approaches: A review," *IEEE Syst. J.*, vol. 16, no. 1, pp. 1391–1399, Jan. 2021.

[69] A. G. R. Ramírez, M. Nandayapa, O. O. V. Villegas, and F. G. Luna, "Haptic augmentation towards a smart learning environment: The haptic lever design," *IEEE Access*, vol. 8, pp. 78467–78481, 2020.

[70] C. Themelis and J.-A. Sime, "From video-conferencing to holoportation and haptics: How emerging technologies can enhance presence in online education?" in *Emerging Technologies and Pedagogies in the Curriculum*. Berlin, Germany: Springer, 2020, pp. 261–276.

[71] J. Ashby, I. Ndayishimiye, A. Muhumuza, and S. Niyoyita, "Digital medical school: New paradigms for tomorrow's surgical education," in *Digital Surgery*. Cham, Switzerland: Springer, 2021, pp. 379–387.

[72] A. W. K. Yeung, A. Tosevska, E. Klager, F. Eibensteiner, D. Laxar, J. Stoyanov, M. Glisic, S. Zeiner, S. T. Kulnik, R. Crutzen, and O. Kimberger, "Virtual and augmented reality applications in medicine: Analysis of the scientific literature," *J. Med. Internet Res.*, vol. 23, no. 2, Feb. 2021, Art. no. e25499.

[73] K. B. Chen, M. E. Sesto, K. Ponto, J. Leonard, A. Mason, G. Vanderheiden, J. Williams, and R. G. Radwin, "Use of virtual reality feedback for patients with chronic neck pain and kinesiophobia," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 8, pp. 1240–1248, Oct. 2016.

[74] Y. Jebbar, F. Belqasmi, R. Glitho, and O. Alfandi, "A fog-based architecture for remote phobia treatment," in *Proc. IEEE Int. Conf. Cloud Comput. Technol. Sci. (CloudCom)*, Dec. 2019, pp. 271–278.

[75] F. Hofmann, N. Franchi, G. Fettweis, A. H. Mahdi, N. Brahmi, B. Wegmann, M. Muehleisen, F. Petry, S. Mudriievskyi, A. El Assaad, and G. Jornod, "5G NetMobil: Pathways towards tactile connected driving," in *Proc. IEEE 2nd 5G World Forum (GWF)*, Sep. 2019, pp. 114–119.

[76] A. Benloucif, A.-T. Nguyen, C. Sentouh, and J.-C. Popieul, "Cooperative trajectory planning for haptic shared control between driver and automation in highway driving," *IEEE Trans. Ind. Electron.*, vol. 66, no. 12, pp. 9846–9857, Dec. 2019.

[77] S. Tanwar, S. Tyagi, I. Budhiraja, and N. Kumar, "Tactile internet for autonomous vehicles: Latency and reliability analysis," *IEEE Wireless Commun.*, vol. 26, no. 4, pp. 66–72, Aug. 2019.

[78] W. Li, L. Ding, H. Gao, and M. Tavakoli, "Haptic tele-driving of wheeled mobile robots under nonideal wheel rolling, kinematic control and communication time delay," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 50, no. 1, pp. 336–347, Aug. 2017.

[79] C. Grasso and G. Schembra, "Design of a UAV-based videosurveillance system with tactile internet constraints in a 5G ecosystem," in *Proc. 4th IEEE Conf. Netw. Softwarization Workshops (NetSoft)*, Jun. 2018, pp. 449–455.

[80] R. Gupta, A. Shukla, and S. Tanwar, "BATS: A blockchain and AI-empowered drone-assisted telesurgery system towards 6G," *IEEE Trans. Netw. Sci. Eng.*, vol. 8, no. 4, pp. 2958–2967, Dec. 2020.

[81] X. Wei, Q. Duan, and L. Zhou, "A QoE-driven tactile internet architecture for smart city," *IEEE Netw.*, vol. 34, no. 1, pp. 130–136, Sep. 2019.

[82] T. M. Ho, T. D. Tran, T. T. Nguyen, S. M. A. Kazmi, L. B. Le, C. S. Hong, and L. Hanzo, "Next-generation wireless solutions for the smart factory, smart vehicles, the smart grid and smart cities," 2019, *arXiv:1907.10102*.

[83] S. H. Alsamhi, O. Ma, M. S. Ansari, and F. A. Almalki, "Survey on collaborative smart drones and Internet of Things for improving smartness of smart cities," *IEEE Access*, vol. 7, pp. 128125–128152, 2019.

[84] O. Madamori, E. Max-Onakpoya, G. D. Erhardt, and C. E. Baker, "Enabling opportunistic low-cost smart cities by using tactical edge node placement," 2021, *arXiv:2103.09860*.

[85] K. A. Awan, I. U. Din, A. Almogren, and H. Almajed, "Agritrust—A trust management approach for smart agriculture in cloud-based internet of agriculture things," *Sensors*, vol. 20, no. 21, p. 6174, Oct. 2020.

[86] A.-T. Braun, E. Colangelo, and T. Steckel, "Farming in the era of Industrie 4.0," in *Proc. CIRP*, vol. 72, Jan. 2018, pp. 979–984.

[87] E. C. Strinati, S. Barbarossa, J. L. Gonzalez-Jimenez, D. Ktenas, N. Cassiau, L. Maret, and C. Dehos, "6G: The next frontier: From holographic messaging to artificial intelligence using subterahertz and visible light communication," *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 42–50, Sep. 2019.

[88] K. Sheth, K. Patel, H. Shah, S. Tanwar, R. Gupta, and N. Kumar, "A taxonomy of AI techniques for 6G communication networks," *Comput. Commun.*, vol. 161, pp. 279–303, Sep. 2020.

[89] M. Shahbazi, S. F. Atashzar, and R. V. Patel, "A systematic review of multilateral teleoperation systems," *IEEE Trans. Haptics*, vol. 11, no. 3, pp. 338–356, Jul. 2018.

[90] T. B. Sheridan, "Space teleoperation through time delay: Review and prognosis," *IEEE Trans. Robot. Autom.*, vol. 9, no. 5, pp. 592–606, Oct. 1993.

[91] A. H. Sodhro, Z. Luo, A. K. Sangaiah, and S. W. Baik, "Mobile edge computing based QoS optimization in medical healthcare applications," *Int. J. Inf. Manage.*, vol. 45, pp. 308–318, Apr. 2019.

[92] A. Bhardwaj, S. Chaudhuri, and O. Dabeer, "Design and analysis of predictive sampling of haptic signals," *ACM Trans. Appl. Perception*, vol. 11, no. 4, pp. 1–20, Dec. 2014.

[93] C. She, C. Yang, and T. Q. S. Quek, "Cross-layer transmission design for tactile internet," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2016, pp. 1–6.

[94] C. She, C. Yang, and T. Q. S. Quek, "Cross-layer optimization for ultra-reliable and low-latency radio access networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 1, pp. 127–141, Oct. 2017.

[95] P. J. Braun, S. Pandi, R.-S. Schmoll, and F. H. P. Fitzek, "On the study and deployment of mobile edge cloud for tactile internet using a 5G gaming application," in *Proc. 14th IEEE Annu. Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2017, pp. 154–159.

[96] V. Petrov, M. A. Lema, M. Gapeyenko, K. Antonakoglou, D. Moltchanov, F. Sardis, A. Samuylov, S. Andreev, Y. Koucheryavy, and M. Dohler, "Achieving end-to-end reliability of mission-critical traffic in softwarized 5G networks," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 3, pp. 485–501, Mar. 2018.

[97] F. Gabriel, J. Acevedo, and F. H. Fitzek, "Network coding on wireless multipath for tactile internet with latency and resilience requirements," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2018, pp. 1–6.

[98] J. A. Cabrera, R.-S. Schmoll, G. T. Nguyen, S. Pandi, and F. H. P. Fitzek, "Softwarization and network coding in the mobile edge cloud for the tactile internet," *Proc. IEEE*, vol. 107, no. 2, pp. 350–363, Feb. 2018.

[99] C. She, Z. Chen, C. Yang, T. Q. S. Quek, Y. Li, and B. Vucetic, "Improving network availability of ultra-reliable and low-latency communications with multi-connectivity," *IEEE Trans. Commun.*, vol. 66, no. 11, pp. 5482–5496, Nov. 2018.

[100] K. S. Kim, D. K. Kim, C. B. Chae, S. Choi, Y. C. Ko, J. Kim, Y. G. Lim, M. Yang, S. Kim, B. Lim, and K. Lee, "Ultrareliable and low-latency communication techniques for tactile internet services," *Proc. IEEE*, vol. 107, no. 2, pp. 376–393, Sep. 2018.

[101] N. Gholipoor, H. Saeedi, and N. Mokari, "Cross-layer resource allocation for mixed tactile internet and traditional data in SCMA based wireless networks," in *Proc. IEEE Wireless Commun. Netw. Conf. Workshops (WCNCW)*, Apr. 2018, pp. 356–361.

[102] H.-T. Chien, Y.-D. Lin, C.-L. Lai, and C.-T. Wang, "End-to-end slicing with optimized communication and computing resource allocation in multi-tenant 5G systems," *IEEE Trans. Veh. Technol.*, vol. 69, no. 2, pp. 2079–2091, Dec. 2019.

[103] J. Xu, K. Ota, and M. Dong, "Energy efficient hybrid edge caching scheme for tactile internet in 5G," *IEEE Trans. Green Commun. Netw.*, vol. 3, no. 2, pp. 483–493, Jun. 2019.

[104] J. Zeng, T. Lv, Z. Lin, R. P. Liu, J. Mei, W. Ni, and Y. J. Guo, "Achieving ultrareliable and low-latency communications in IoT by FD-SCMA," *IEEE Internet Things J.*, vol. 7, no. 1, pp. 363–378, Oct. 2019.

[105] Z. Xiang, F. Gabriel, E. Urbano, G. T. Nguyen, M. Reisslein, and F. H. P. Fitzek, "Reducing latency in virtual machines: Enabling tactile internet for human-machine co-working," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 5, pp. 1098–1116, May 2019.

[106] M. Maier and A. Ebrahimzadeh, "Towards immersive tactile internet experiences: Low-latency FiWi enhanced mobile networks with edge intelligence," *J. Opt. Commun. Netw.*, vol. 11, no. 4, pp. B10–B25, Apr. 2019.

[107] N. Gholipoor, S. Parsaeefard, M. R. Javan, N. Mokari, H. Saeedi, and H. Pishro-Nik, "Resource management and admission control for tactile internet in next generation of radio access network," *IEEE Access*, vol. 8, pp. 136261–136277, 2020.

[108] W. Yang, C.-P. Li, A. Fakoorian, K. Hosseini, and W. Chen, "Dynamic URLLC and eMBB multiplexing design in 5G new radio," in *Proc. IEEE 17th Annu. Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2020, pp. 1–5.

[109] P. Yang, X. Xi, T. Q. S. Quek, and H. Shin, "CoMP-enabled RAN slicing for tactile internet," 2021, *arXiv:2103.09532*.

[110] A. K. Permana and E. Y. Hamid, "Performance evaluation of GFDM channel estimation using DFT for tactile internet application," *Electronics*, vol. 10, no. 5, p. 595, Mar. 2021.

[111] "5G; service requirements for cyber-physical control applications in vertical domains," 3GPP, Release 16, Tech. Rep. 122104, 2022, pp. 1–78.

[112] X. Liu, M. Dohler, and Y. Deng, "Vibrotactile quality assessment: Hybrid metric design based on SNR and SSIM," *IEEE Trans. Multimedia*, vol. 22, no. 4, pp. 921–933, Aug. 2019.

[113] E. Muschter, A. Noll, J. Zhao, R. Hassen, M. Strese, B. Gulecyuz, S.-C. Li, and E. Steinbach, "Perceptual quality assessment of compressed vibrotactile signals through comparative judgment," *IEEE Trans. Haptics*, vol. 14, no. 2, pp. 291–296, Apr. 2021.

[114] N. Sakr, N. D. Georganas, and J. Zhao, "A perceptual quality metric for haptic signals," in *Proc. IEEE Int. Workshop Haptic, Audio Vis. Environ. Games*, Oct. 2007, pp. 27–32.

[115] R. Chaudhari, E. Steinbach, and S. Hirche, "Towards an objective quality evaluation framework for haptic data reduction," in *Proc. IEEE World Haptics Conf.*, Jun. 2011, pp. 539–544.

[116] R. Hassen and E. Steinbach, "HSSIM: An objective haptic quality assessment measure for force-feedback signals," in *Proc. 10th Int. Conf. Quality Multimedia Exper. (QoMEX)*, May 2018, pp. 1–6.

[117] R. Hassen and E. Steinbach, "Subjective evaluation of the spectral temporal SIMilarity (ST-SIM) measure for vibrotactile quality assessment," *IEEE Trans. Haptics*, vol. 13, no. 1, pp. 25–31, Dec. 2019.

[118] Y. Xu, Y. Huang, W. Chen, H. Xue, and T. Zhao, "Error resilience of haptic data in interactive systems," in *Proc. 11th Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2019, pp. 1–6.

[119] L. Qian and Z. Tiesong, "Quality-of-experience in human-in-the-loop haptic communications," *ZTE Commun.*, vol. 17, no. 1, pp. 48–55, Nov. 2019.

[120] E. Steinbach, M. Strese, M. Eid, X. Liu, A. Bhardwaj, Q. Liu, M. Al-Ja'Afreh, T. Mahmoodi, R. Hassen, A. El Saddik, and O. Holland, "Haptic codecs for the tactile internet," *Proc. IEEE*, vol. 107, no. 2, pp. 447–470, Sep. 2018.

[121] P. Goudarzi, "A fuzzy admission control scheme for high quality video delivery over underlay cognitive radio," *Phys. Commun.*, vol. 7, pp. 134–144, Jun. 2013.

[122] *Performance and Quality of Service Requirements for International Mobile Telecommunications-2000 (IMT-2000) Access Networks*, document 1079-2, U. Recomendation, 2003.

[123] *Methodologies for the Subjective Assessment of the Quality of Television Images, Document Recommendation ITU-R BT. 500-14 (10/2019)*, document ITU-R BT.500-14 (10/2019), Geneva, Switzerland, 2020.

[124] J. Li, L. Zhao, A. Li, B. Kang, and M. Chen, "QoE- driven tactile internet: Scenario, architecture and analysis," in *Proc. 13th Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2021, pp. 1–6.

[125] M. Jalil Piran, Q.-V. Pham, S. M. R. Islam, S. Cho, B. Bae, D. Y. Suh, and Z. Han, "Multimedia communication over cognitive radio networks from QoS/QoE perspective: A comprehensive survey," *J. Netw. Comput. Appl.*, vol. 172, Dec. 2020, Art. no. 102759.

[126] J. B. Van Erp, K.-U. Kyung, S. Kassner, J. Carter, S. Brewster, G. Weber, and I. Andrew, "Setting the standards for haptic and tactile interactions: ISO's work," in *Proc. Int. Conf. on Hum. Haptic Sens. Touch Enabled Comput. Appl.* Berlin, Germany: Springer, 2010, pp. 353–358.

[127] S. Chaudhuri and A. Bhardwaj, "Perceptual deadzone," in *Kinesthetic Perception*. Singapore: Springer, 2018, pp. 17–28.

[128] S. Chaudhuri and A. Bhardwaj, "Predictive sampler design for haptic signals," in *Kinesthetic Perception*. Singapore: Springer, 2018, pp. 29–53.

[129] T. Nakano, S. Uozumi, R. Johansson, and K. Ohnishi, "A quantization method for haptic data lossy compression," in *Proc. IEEE Int. Conf. Mechatronics (ICM)*, Mar. 2015, pp. 126–131.

[130] A. Kuzu, E. A. Baran, S. Bogosyan, M. Gokasan, and A. Sabanovic, "Wavelet packet transform-based compression for teleoperation," *Proc. Inst. Mech. Eng., I, J. Syst. Control Eng.*, vol. 229, no. 7, pp. 639–651, Aug. 2015.

[131] E. A. Baran, A. Kuzu, S. Bogosyan, M. Gokasan, and A. Sabanovic, "Comparative analysis of a selected DCT-based compression scheme for haptic data transmission," *IEEE Trans. Ind. Informat.*, vol. 12, no. 3, pp. 1146–1155, Jun. 2016.

[132] C. Zeng, T. Zhao, Q. Liu, Y. Xu, and K. Wang, "Perception-lossless codec of haptic data with low delay," in *Proc. 28th ACM Int. Conf. Multimedia*, Oct. 2020, pp. 3642–3650.

[133] A. Noll, B. Gulecyuz, A. Hofmann, and E. Steinbach, "A rate-scalable perceptual wavelet-based vibrotactile codec," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Mar. 2020, pp. 854–859.

[134] R. Hassen and E. Steinbach, "Vibrotactile signal compression based on sparse linear prediction and human tactile sensitivity function," in *Proc. IEEE World Haptics Conf. (WHC)*, Jul. 2019, pp. 301–306.

[135] P. Seeling, M. Reisslein, and F. H. P. Fitzek, "Real-time compression for tactile internet data streams," *Sensors*, vol. 21, no. 5, p. 1924, Mar. 2021.

[136] M. Gui, X. Xu, and E. Steinbach, "Adaptive packet rate control for the mitigation of bursty haptic traffic in teleoperation systems," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Mar. 2020, pp. 134–139.

[137] S. Kakade and S. Chaudhuri, "Perceptually compressive communication of interactive telehaptic signal," in *Proc. Int. Conf. Hum. Haptic Sens. Touch Enabled Comput. Appl.* Cham, Switzerland: Springer, 2020, pp. 480–488.

[138] V. Gokhale, J. Nair, and S. Chaudhuri, "Opportunistic adaptive haptic sampling on forward channel in telehaptic communication," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Apr. 2016, pp. 217–222.

[139] P. De Luca and A. Formisano, "Haptic data accelerated prediction via multicore implementation," in *Proc. Sci. Inf. Conf.* Cham, Switzerland: Springer, 2020, pp. 110–121.

[140] R. Hassen, B. Gulecyuz, and E. Steinbach, "PVC-SLP: Perceptual vibrotactile-signal compression based-on sparse linear prediction," *IEEE Trans. Multimedia*, vol. 23, pp. 4455–4468, 2020.

[141] X. Liu and M. Dohler, "A data-driven approach to vibrotactile data compression," in *Proc. IEEE Int. Workshop Signal Process. Syst. (SIPS)*, Oct. 2019, pp. 341–346.

[142] Z. Li, R. Hassen, and Z. Wang, "Autoencoder for vibrotactile signal compression," in *Proc. ICASSP*, Jun. 2021, pp. 4290–4294.

[143] J. Kirsch, A. Noll, M. Strese, Q. Liu, and E. Steinbach, "A low-cost acquisition, display, and evaluation setup for tactile codec development," in *Proc. IEEE Int. Symp. Haptic, Audio Vis. Environ. Games (HAVE)*, Sep. 2018, pp. 1–6.

[144] M. Strese, L. Brudermueller, J. Kirsch, and E. Steinbach, "Haptic material analysis and classification inspired by human exploratory procedures," *IEEE Trans. Haptics*, vol. 13, no. 2, pp. 404–424, Nov. 2019.

[145] S. Lichiardopol, "A survey on teleoperation," Technische Universitat Eindhoven, Eindhoven, The Netherlands, DCT Rep. 2007.155, 2007, pp. 40–60, vol. 20.

[146] C. Passenberg, A. Peer, and M. Buss, "A survey of environment−, operator−, and task-adapted controllers for teleoperation systems," *Mechatronics*, vol. 20, no. 7, pp. 787–801, Oct. 2010.

[147] T. A. Varkonyi, I. J. Rudas, P. Pausits, and T. Haidegger, "Survey on the control of time delay teleoperation systems," in *Proc. IEEE 18th Int. Conf. Intell. Eng. Syst. (INES)*, Jul. 2014, pp. 89–94.

[148] P. M. Kebria, H. Abdi, M. M. Dalvand, A. Khosravi, and S. Nahavandi, "Control methods for internet-based teleoperation systems: A review," *IEEE Trans. Human-Mach. Syst.*, vol. 49, no. 1, pp. 32–46, Nov. 2018.

[149] P. Arcara and C. Melchiorri, "Control schemes for teleoperation with time delay: A comparative study," *Robot. Auto. Syst.*, vol. 38, no. 1, pp. 49–64, Jan. 2002.

[150] G. Bauer and Y.-J. Pan, "Review of control methods for upper limb telerehabilitation with robotic exoskeletons," *IEEE Access*, vol. 8, pp. 203382–203397, 2020.

[151] B. Brogliato, R. Lozano, B. Maschke, and O. Egeland, "Dissipative systems analysis and control," in *Theory and Applications*, vol. 2. Cham, Switzerland: Springer, 2007.

[152] E. Nuño, L. Basañez, and R. Ortega, "Passivity-based control for bilateral teleoperation: A tutorial," *Automatica*, vol. 47, no. 3, pp. 485–495, Mar. 2011.

[153] G. Niemeyer and J. Slotine, "Stable adaptive teleoperation," *IEEE J. Ocean. Eng.*, vol. 522, no. 1, pp. 152–162, Jan. 1991.

[154] D. Sun, F. Naghdy, and H. Du, "Application of wave-variable control to bilateral teleoperation systems: A survey," *Annu. Rev. Control*, vol. 38, no. 1, pp. 12–31, Jan. 2014.

[155] D. Tian, B. Zhang, H. Shen, and J. Li, "Stability problem of wave variable based bilateral control: Influence of the force source design," *Math. Problems Eng.*, vol. 2013, Jan. 2013, Art. no. 105298.

[156] L. Bate, C. D. Cook, and Z. Li, "Reducing wave-based teleoperator reflections for unknown environments," *IEEE Trans. Ind. Electron.*, vol. 58, no. 2, pp. 392–397, Nov. 2009.

[157] M. Zheng, Q.-H. Chen, W. Xiao, and H.-N. Yang, "Bilateral teleoperation with reducing wave-based reflections," *Adv. Manuf.*, vol. 1, no. 3, pp. 288–292, Sep. 2013.

[158] J. Guo, C. Liu, and P. Poignet, "A scaled bilateral teleoperation system for robotic-assisted surgery with time delay," *J. Intell. Robot. Syst.*, vol. 95, no. 1, pp. 165–192, Jul. 2019.

[159] N. D'Amore and D. L. Akin, "Transparency and tuning of wave-based bilateral teleoperation systems," *IEEE Robot. Autom. Lett.*, vol. 2, no. 1, pp. 321–328, Sep. 2016.

[160] F. E. Mujčić and S. A. Oračević, "Internet based teleoperations with using wave variables," *IFAC Proc. Volumes*, vol. 45, no. 7, pp. 255–260, Jan. 2012.

[161] B. Chen, Y. Guo, and Y. Wu, "Comparative study of wave-variables and Smith predictor for teleoperator force-position control," in *Proc. Chin. Control Decis. Conf. (CCDC)*, Jun. 2019, pp. 2960–2964.

[162] Y. Kawai, K. Honda, H. Kawai, T. Miyoshi, and M. Fujita, "Telerehabilitation system for human lower limb using electrical stimulation based on bilateral teleoperation," in *Proc. IEEE Conf. Control Technol. Appl. (CCTA)*, Aug. 2017, pp. 1446–1451.

[163] C. Yang, X. Wang, Z. Li, Y. Li, and C.-Y. Su, "Teleoperation control based on combination of wave variable and neural networks," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 47, no. 8, pp. 2125–2136, Oct. 2016.

[164] E. Mujcic, A. Mujcic, and S. Pajazetovic, "Internet-based teleoperation using wave variables and correction of position error," in *Proc. Int. Conf. Smart Syst. Technol. (SST)*, Oct. 2016, pp. 219–224.

[165] J. Luo, C. Liu, N. Wang, and C. Yang, "A wave variable approach with multiple channel architecture for teleoperated system," *IEEE Access*, vol. 7, pp. 143912–143920, 2019.

[166] Z. Chen, F. Huang, W. Sun, and W. Song, "An improved wave-variable based four-channel control design in bilateral teleoperation system for time-delay compensation," *IEEE Access*, vol. 6, pp. 12848–12857, 2018.

[167] Z. Chen, F. Huang, W. Song, and S. Zhu, "A novel wave-variable based time-delay compensated four-channel control design for multilateral teleoperation system," *IEEE Access*, vol. 6, pp. 25506–25516, 2018.

[168] D. Sun, F. Naghdy, and H. Du, "Stability control of force-reflected nonlinear multilateral teleoperation system under time-varying delays," *J. Sensors*, vol. 2016, Mar. 2016, Art. no. 4316024.

[169] P. Huang, P. Dai, Z. Lu, and Z. Liu, "Asymmetric wave variable compensation method in dual-master-dual-slave multilateral teleoperation system," *Mechatronics*, vol. 49, pp. 1–10, Feb. 2018.

[170] X. Xu and E. Steinbach, "Elimination of cross-dimensional artifacts in the multi-dof time domain passivity approach for time-delayed teleoperation with haptic feedback," in *Proc. IEEE World Haptics Conf. (WHC)*, Jul. 2019, pp. 223–228.

[171] D. Sun, F. Naghdy, and H. Du, "Neural network-based passivity control of teleoperation system under time-varying delays," *IEEE Trans. Cybern.*, vol. 47, no. 7, pp. 1666–1680, Apr. 2016.

[172] S. F. Atashzar, M. Shahbazi, M. Tavakoli, and R. V. Patel, "A passivity-based approach for stable patient–robot interaction in haptics-enabled rehabilitation systems: Modulated time-domain passivity control," *IEEE Trans. Control Syst. Technol.*, vol. 25, no. 3, pp. 991–1006, Aug. 2016.

[173] D. Buongiorno, D. Chiaradia, S. Marcheschi, M. Solazzi, and A. Frisoli, "Multi-DoFs exoskeleton-based bilateral teleoperation with the time-domain passivity approach," *Robotica*, vol. 37, no. 9, pp. 1641–1662, Sep. 2019.

[174] F. Porcini, D. Chiaradia, S. Marcheschi, M. Solazzi, and A. Frisoli, "Evaluation of an exoskeleton-based bimanual teleoperation architecture with independently passivated slave devices," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2020, pp. 10205–10211.

[175] F. Hashemzadeh, I. Hassanzadeh, M. Tavakoli, and G. Alizadeh, "Adaptive control for state synchronization of nonlinear haptic telerobotic systems with asymmetric varying time delays," *J. Intell. Robot. Syst.*, vol. 68, nos. 3–4, pp. 245–259, Dec. 2012.

[176] S. Forbrigger and Y.-J. Pan, "Improving haptic transparency for uncertain virtual environments using adaptive control and gain-scheduled prediction," *IEEE Trans. Haptics*, vol. 11, no. 4, pp. 543–554, Oct. 2018.

[177] U. J. Na, "A new impedance force control of a haptic teleoperation system for improved transparency," *J. Mech. Sci. Technol.*, vol. 31, no. 12, pp. 6005–6017, Dec. 2017.

[178] L. Hu, J. Li, X. Liu, P. Xiong, and S. He, "The maximum output force controller and its application to a virtual surgery system," *Int. J. Adv. Robot. Syst.*, vol. 15, no. 2, Mar. 2018, Art. no. 1729881418765884.

[179] S. Hao, L. Hu, and P. X. Liu, "Sliding mode control for a surgical teleoperation system via a disturbance observer," *IEEE Access*, vol. 7, pp. 43383–43393, 2019.

[180] V. K. Pediredla, S. Annamraju, and A. Thondiyath, "Enhancement of high-fidelity haptic feedback through multimodal adaptive robust control for teleoperated systems," *IEEE Syst. J.*, vol. 15, no. 4, pp. 5526–5536, Nov. 2020.

[181] J. Guo, P. Li, H. Yan, and H. Ren, "Viscoelastic model based bilateral teleoperation for robotic-assisted tele-palpation," *Assem. Autom.*, vol. 37, no. 3, pp. 322–334, Aug. 2017.

[182] C. Liu, J. Guo, and P. Poignet, "Nonlinear model-mediated teleoperation for surgical applications under time variant communication delay," *IFAC-PapersOnLine*, vol. 51, no. 22, pp. 493–499, Jan. 2018.

[183] J. Song, Y. Ding, Z. Shang, and J. Liang, "Model-mediated teleoperation with improved stability," *Int. J. Adv. Robot. Syst.*, vol. 15, no. 2, Mar. 2018, Art. no. 1729881418761136.

[184] B. Yazdankhoo and B. Beigzadeh, "Increasing stability in model-mediated teleoperation approach by reducing model jump effect," *Scientia Iranica*, vol. 26, no. 1, pp. 3–14, Jan./Feb. 2019.

[185] B. Hannaford and J.-H. Ryu, "Time-domain passivity control of haptic interfaces," *IEEE Trans. Robot. Autom.*, vol. 18, no. 1, pp. 1–10, Feb. 2002.

[186] R. Balachandran, J. Artigas, U. Mehmood, and J.-H. Ryu, "Performance comparison of wave variable transformation and time domain passivity approaches for time-delayed teleoperation: Preliminary results," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2016, pp. 410–417.

[187] J.-H. Ryu, J. Artigas, and C. Preusche, "A passive bilateral control scheme for a teleoperator with time-varying communication delay," *Mechatronics*, vol. 20, no. 7, pp. 812–823, Oct. 2010.

[188] Y. Ye, Y.-J. Pan, and T. Hilliard, "Bilateral teleoperation with time-varying delay: A communication channel passification approach," *IEEE/ASME Trans. Mechatronics*, vol. 18, no. 4, pp. 1431–1434, Aug. 2013.

[189] V. Chawda and M. K. O'Malley, "Position synchronization in bilateral teleoperation under time-varying communication delays," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 1, pp. 245–253, May 2014.

[190] K. Hashtrudi-Zaad and S. E. Salcudean, "Analysis of control architectures for teleoperation systems with impedance/admittance master and slave manipulators," *Int. J. Robot. Res.*, vol. 20, no. 6, pp. 419–445, Jun. 2001.

[191] Y. Sang Kim and B. Hannaford, "Some practical issues in time domain passivity control of haptic interfaces," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst., Expanding Societal Role Robot. Next Millennium*, vol. 3, Oct./Nov. 2001, pp. 1744–1750.

[192] J.-H. Ryu, "Bilateral control with time domain passivity approach under time-varying communication delay," in *Proc. 16th IEEE Int. Symp. Robot Human Interact. Commun. (RO-MAN)*, Aug. 2007, pp. 986–991.

[193] U. Ahmad and Y.-J. Pan, "Switching time domain passivity control for multilateral teleoperation systems under time varying delays," in *Proc. IEEE 55th Conf. Decis. Control (CDC)*, Dec. 2016, pp. 1429–1434.

[194] J.-H. Ryu, Q. Ha-Van, and A. Jafari, "Multilateral teleoperation over communication time delay using the time-domain passivity approach," *IEEE Trans. Control Syst. Technol.*, vol. 28, no. 6, pp. 2705–2712, Nov. 2019.

[195] L. Chan, F. Naghdy, and D. Stirling, "Application of adaptive controllers in teleoperation systems: A survey," *IEEE Trans. Human-Mach. Syst.*, vol. 44, no. 3, pp. 337–352, Jun. 2014.

[196] S. Hirche and M. Buss, "Human-oriented control for haptic teleoperation," *Proc. IEEE*, vol. 100, no. 3, pp. 623–647, Mar. 2012.

[197] B. Hannaford, "A design framework for teleoperators with kinesthetic feedback," *IEEE Trans. Robot. Autom.*, vol. 5, no. 4, pp. 426–434, Aug. 1989.

[198] P. Mitra and G. Niemeyer, "Model-mediated telemanipulation," *Int. J. Robot. Res.*, vol. 27, no. 2, pp. 253–262, Feb. 2008.

[199] X. Xu, B. Cizmeci, C. Schuwerk, and E. Steinbach, "Model-mediated teleoperation: Toward stable and transparent teleoperation systems," *IEEE Access*, vol. 4, pp. 425–449, 2016.

[200] X. Xu, B. Cizmeci, A. Al-Nuaimi, and E. Steinbach, "Point cloud-based model-mediated teleoperation with dynamic and perception-based model updating," *IEEE Trans. Instrum. Meas.*, vol. 63, no. 11, pp. 2558–2569, May 2014.

[201] X. Xu, Q. Liu, and E. Steinbach, "Toward QoE-driven dynamic control scheme switching for time-delayed teleoperation systems: A dedicated case study," in *Proc. IEEE Int. Symp. Haptic, Audio Vis. Environ. Games (HAVE)*, Oct. 2017, pp. 1–6.

[202] X. Xu, Q. Liu, and E. Steinbach, "Haptic data reduction for time-delayed teleoperation using the input-to-state stability approach," in *Proc. IEEE World Haptics Conf. (WHC)*, Jul. 2019, pp. 533–538.

[203] X. Xu, M. Panzirsch, Q. Liu, and E. Steinbach, "Integrating haptic data reduction with energy reflection-based passivity control for time-delayed teleoperation," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Mar. 2020, pp. 109–114.

[204] Q. Deng, T. Faghanimakrani, and A. H. Aghvami, "GBDT-based modules for force prediction in a model-mediated teleoperation system," in *Proc. 27th Int. Conf. Telecommun. (ICT)*, Oct. 2020, pp. 1–6.

[205] D. Sun, F. Naghdy, and H. Du, "Time domain passivity control of time-delayed bilateral telerobotics with prescribed performance," *Nonlinear Dyn.*, vol. 87, no. 2, pp. 1253–1270, Jan. 2017.

[206] M. Panzirsch, J.-H. Ryu, and M. Ferre, "Reducing the conservatism of the time domain passivity approach through consideration of energy reflection in delayed coupled network systems," *Mechatronics*, vol. 58, pp. 58–69, Apr. 2019.

[207] L. Ruan, M. P. I. Dias, and E. Wong, "Enhancing latency performance through intelligent bandwidth allocation decisions: A survey and comparative study of machine learning techniques," *J. Opt. Commun. Netw.*, vol. 12, no. 4, pp. B20–B32, 2020.

[208] L. Ruan, S. Mondal, I. Dias, and E. Wong, "Low-latency federated reinforcement learning-based resource allocation in converged access networks," in *Proc. Opt. Fiber Commun. Conf. (OFC)*, Mar. 2020. Paper W2A–28.

[209] N. Sakr, J. Zhou, N. D. Georganas, and J. Zhao, "Prediction-based haptic data reduction and transmission in telementoring systems," *IEEE Trans. Instrum. Meas.*, vol. 58, no. 5, pp. 1727–1736, Dec. 2008.

[210] Y. Kusunose, Y. Ishibashi, N. Fukushima, and S. Sugawara, "Adaptive delta-causality control with prediction in networked real-time game using haptic media," in *Proc. 18th Asia–Pacific Conf. Commun. (APCC)*, Oct. 2012, pp. 800–805.

[211] B. Yazdankhoo, M. Nikpour, B. Beigzadeh, and A. Meghdari, "Improvement of operator position prediction in teleoperation systems with time delay: Simulation and experimental studies on phantom omni devices," *Jordan J. Mech. Ind. Eng.*, vol. 13, no. 3, pp. 197–205, Oct. 2019.

[212] M. Nikpour, B. Yazdankhoo, B. Beigzadeh, and A. Meghdari, "Adaptive online prediction of operator position in teleoperation with unknown time-varying delay: Simulation and experiments," *Neural Comput. Appl.*, vol. 33, no. 13, pp. 1–18, Nov. 2020.

[213] H.-S. Moon and J. Seo, "Prediction of human trajectory following a haptic robotic guide using recurrent neural networks," in *Proc. IEEE World Haptics Conf. (WHC)*, Jul. 2019, pp. 157–162.

[214] K. M. Yap, T. H. Tee, A. Marshall, K. S. Eu, Y. K. Lee, T.-H. Lee, P. H. Lim, and Y. Chook, "A network-adaptive prediction algorithm for haptic data under network impairments," *IEEE Access*, vol. 9, pp. 52672–52683, 2021.

[215] L. Cheng and M. Tavakoli, "Neural network-based physiological organ motion prediction and robot impedance control for teleoperated beating-heart surgery," *Biomed. Signal Process. Control*, vol. 66, Apr. 2021, Art. no. 102423.

[216] S. Mondal, L. Ruan, and E. Wong, "Remote human-to-machine distance emulation through AI-enhanced servers for tactile internet applications," in *Proc. Opt. Fiber Commun. Conf. (OFC)*, Mar. 2020, pp. 1–3, Paper M1A–6.

[217] E. Wong, S. Mondal, and L. Ruan, "Alleviating the master-slave distance limitation in H2M communications through remote environment emulation," in *Proc. Int. Conf. Opt. Netw. Design Modeling (ONDM)*, May 2020, pp. 1–3.

[218] S. Mondal, L. Ruan, M. Maier, D. Larrabeiti, G. Das, and E. Wong, "Enabling remote human-to-machine applications with AI-enhanced servers over access networks," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 889–899, 2020.

[219] F. Rasouli, A. Ebrahimzadeh, S. Kianpisheh, N. Promwongsa, F. Belqasmi, and R. Glitho, "A predictive framework for haptic enabled VR-based remote phobia treatment in cloud/fog environment," in *Proc. 24th Conf. Innov. Clouds, Internet Netw. Workshops (ICIN)*, Mar. 2021, pp. 20–27.

[220] C. J. Perez-del-Pulgar, J. Smisek, V. F. Munoz, and A. Schiele, "Using learning from demonstration to generate real-time guidance for haptic shared control," in *Proc. IEEE Int. Conf. Syst., Man, Cybern. (SMC)*, Oct. 2016, pp. 003205–003210.

[221] C. J. Pérez-del-Pulgar, J. Smisek, I. Rivas-Blanco, A. Schiele, and V. F. Muñoz, "Using Gaussian mixture models for gesture recognition during haptically guided telemanipulation," *Electronics*, vol. 8, no. 7, p. 772, Jul. 2019.

[222] F. Boabang, R. Glitho, H. Elbiaze, F. Belqami, and O. Alfandi, "A framework for predicting haptic feedback in needle insertion in 5G remote robotic surgery," in *Proc. IEEE 17th Annu. Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2020, pp. 1–6.

[223] L. C. Mutalemwa and S. Shin, "A classification of the enabling techniques for low latency and reliable communications in 5G and beyond: Ai-enabled edge caching," *IEEE Access*, vol. 8, pp. 205502–205533, 2020.

[224] J. Luo, W. He, and C. Yang, "Combined perception, control, and learning for teleoperation: Key technologies, applications, and challenges," *Cognit. Comput. Syst.*, vol. 2, no. 2, pp. 33–43, Jun. 2020.

[225] Z. Hou, C. She, Y. Li, D. Niyato, M. Dohler, and B. Vucetic, "Intelligent communications for tactile internet in 6G: Requirements, technologies, and challenges," *IEEE Commun. Mag.*, vol. 59, no. 12, pp. 82–88, Dec. 2021.

[226] H. Culbertson, J. J. L. Delgado, and K. J. Kuchenbecker, "One hundred data-driven haptic texture models and open-source methods for rendering on 3D objects," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Feb. 2014, pp. 319–325.

[227] M. Strese, C. Schuwerk, A. Iepure, and E. Steinbach, "Multimodal feature-based surface material classification," *IEEE Trans. Haptics*, vol. 10, no. 2, pp. 226–239, Nov. 2016.

[228] J. Jiao, Y. Zhang, D. Wang, X. Guo, and X. Sun, "HapTex: A database of fabric textures for surface tactile display," in *Proc. IEEE World Haptics Conf. (WHC)*, Jul. 2019, pp. 331–336.

[229] A. Abdulali, R. Rakhmatov, T. Ogay, and S. Jeon, "Data-driven modeling and rendering of force responses from elastic tool deformation," *Sensors*, vol. 18, no. 1, p. 237, Jan. 2018.

[230] T. L. de Jong, J. Dankelman, and J. J. van den Dobbelsteen, "Dataset on force measurements of needle insertions into two *ex-vivo* human livers," *Data Brief*, vol. 11, pp. 308–310, Apr. 2017.

[231] M. Kerzel, E. Strahl, C. Gaede, E. Gasanov, and S. Wermter, "Neuro-robotic haptic object classification by active exploration on a novel dataset," in *Proc. Int. Joint Conf. Neural Netw. (IJCNN)*, Jul. 2019, pp. 1–8.

[232] T. Bhattacharjee, J. M. Rehg, and C. C. Kemp, "Haptic classification and recognition of objects using a tactile sensing forearm," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2012, pp. 4090–4097.

[233] T. Bhattacharjee, H. Bai, H. Chen, and C. C. Kemp, "A model that predicts the material recognition performance of thermal tactile sensing," 2017, *arXiv:1711.01490*.

[234] M. Strese, J.-Y. Lee, C. Schuwerk, Q. Han, H.-G. Kim, and E. Steinbach, "A haptic texture database for tool-mediated texture recognition and classification," in *Proc. IEEE Int. Symp. Haptic, Audio Vis. Environ. Games (HAVE)*, Oct. 2014, pp. 118–123.

[235] K. Polachan, T. V. Prabhakar, C. Singh, and F. A. Kuipers, "Towards an open testbed for tactile cyber physical systems," in *Proc. 11th Int. Conf. Commun. Syst. Netw. (COMSNETS)*, Jan. 2019, pp. 375–382.

[236] J. J. Fleck, Z. A. Zook, T. W. Tjandra, and M. K. O'Malley, "A cutaneous haptic cue characterization testbed," in *Proc. IEEE World Haptics Conf. (WHC)*, Jul. 2019, pp. 319–324.

[237] V. Gokhale, K. Kroep, V. S. Rao, J. Verburg, and R. Yechangunja, "TIXT: An extensible testbed for tactile internet communication," *IEEE Internet Things Mag.*, vol. 3, no. 1, pp. 32–37, Apr. 2020.

[238] F. Engelhardt, J. Behrens, and M. Gunes, "The OVGU haptic communication testbed (OVGU-HC)," in *Proc. IEEE 31st Annu. Int. Symp. Pers., Indoor Mobile Radio Commun.*, Aug. 2020, pp. 1–6.

[239] A. Noll, A. Gurbuz, B. Gulecyuz, K. Cui, and E. Steinbach, "Quality enhancement of compressed vibrotactile signals using recurrent neural networks and residual learning," *IEEE Trans. Haptics*, vol. 14, no. 2, pp. 316–321, Apr. 2021.

[240] L. Zhou, D. Wu, J. Chen, and X. Wei, "Cross-modal collaborative communications," *IEEE Wireless Commun.*, vol. 27, no. 2, pp. 112–117, Oct. 2019.

[241] L. Zhou, D. Wu, X. Wei, and J. Chen, "Cross-modal stream scheduling for eHealth," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 2, pp. 426–437, Sep. 2020.

[242] M. Simsek, S. Oteafy, Z. Dawy, M. Eid, O. Holland, and E. Steinbach, "Tactile internet standards of the IEEE p1918. 1 working group," in *Tactile Internet*. Amsterdam, The Netherlands: Elsevier, 2021, pp. 351–374.

[243] K. Antonakoglou, M. Mahlouji, and T. Mahmoodi, "Bilateral teleoperation performance model for network resource management," *IEEE Access*, vol. 9, pP. 29106–29117, 2021.

[244] Y. Dong and N. Chopra, "Passivity-based bilateral tele-driving system with parametric uncertainty and communication delays," *IEEE Control Syst. Lett.*, vol. 3, no. 2, pp. 350–355, Mar. 2018.

[245] I. O. Ogunrinde, C. F. Adetu, C. A. Moore, R. G. Roberts, and K. McQueen, "Experimental testing of bandstop wave filter to mitigate wave reflections in bilateral teleoperation," *Robotics*, vol. 9, no. 2, p. 24, Apr. 2020.

[246] X. Tao, J. Li, and Q. Huang, "Stability analysis of time-varying delay bilateral teleoperation system with state prediction," in *Proc. 6th Int. Conf. Control, Autom. Robot. (ICCAR)*, Apr. 2020, pp. 272–276.
[247] C. Thomas, S. Yi, S. Meadows, and R. Sherrill, "Adaptive Smith predictor for teleoperation of UAVs with time-varying internet delay," *Int. J. Control, Autom. Syst.*, vol. 18, no. 6, pp. 1465–1473, Jun. 2020.
[248] M. Dohler, "5G networks, haptic codecs, and the operating theatre," in *Digital Surgery*. Cham, Switzerland: Springer, 2021, pp. 71–86.
[249] D. Budolak and P. Ben-Tzvi, "Series elastic actuation for improved transparency in time delayed haptic teleoperation," *Mechatronics*, vol. 63, Nov. 2019, Art. no. 102278.
[250] Y. Cheng, "Edge caching and computing in 5G for mobile augmented reality and haptic internet," *Comput. Commun.*, vol. 158, pp. 24–31, May 2020.
[251] C. Grasso, K. E. Kn, P. Nagaradjane, M. Ramesh, and G. Schembra, "Designing the tactile support engine to assist time-critical applications at the edge of a 5G network," *Comput. Commun.*, vol. 166, pp. 226–233, Jan. 2021.
[252] F. Brandi, J. Kammerl, and E. Steinbach, "Error-resilient perceptual coding for networked haptic interaction," in *Proc. Int. Conf. Multimedia (MM)*, 2010, pp. 351–360.
[253] Y. Xu, Q. Zheng, Q. Lin, K. Wang, and T. Zhao, "Error resilience algorithm for haptic communication based on remedy-LSTM," in *Proc. IEEE 6th Int. Conf. Comput. Commun. (ICCC)*, Dec. 2020, pp. 2207–2211.
[254] S. Hangai and T. Nozaki, "Haptic data prediction and extrapolation for communication traffic reduction of 4-channel bilateral control system," *IEEE Trans. Ind. Informat.*, vol. 17, no. 4, pp. 2611–2620, May 2020.

MUHAMMAD ZUBAIR ISLAM (Student Member, IEEE) received the B.S. degree in computer science from the University of Agriculture Faisalabad (UAF), Pakistan, in 2017, and the master's degree in information and communication engineering from Sejong University, Seoul, South Korea, in 2020, where he is currently pursuing the Ph.D. degree with the Department of Intelligent Mechatronics Engineering. Along with his study, he is working as a Research Assistant with the Mobile INtelligent Embedded System (MINES) Laboratory, Sejong University. His research interests include applications of artificial intelligence and predictive models in education data mining (EDM), next-generation communication technologies (tactile internet), and edge intelligence.

RASHID ALI (Member, IEEE) received the B.S. degree in information technology from Gomal University, Pakistan, in 2007, the master's degree in computer science (advanced network design) and the master's degree in informatics from University West, Sweden, in 2010 and 2013, respectively, and the Ph.D. Diploma degree in information and communication engineering from the Department of Information and Communication Engineering, Yeungnam University, South Korea, in February 2019. He has worked at the Operations and Research Department, Wateen Telecom Private Ltd., Pakistan, as a WiMAX Executive Engineer, from 2007 and 2009. From July 2013 to June 2014, he has worked for COMSATS University Islamabad (Vehari), Pakistan, as a Lecturer of computer science. For the year 2019–2020, he has achieved a Postdoctoral Research Fellow Scholarship at the Department of Information and Communications Engineering, Yeungnam University, and the School Intelligent Mechatronics Engineering, Sejong University, South Korea. Later, he also worked as an Assistant Professor at the School of Intelligent Mechatronics Engineering, Sejong University, from 2020 to 2021. He is currently working as an EUTOPIA-SIF Research Fellow at the Department of Information and Communication Technologies, Universitat Pompeu Fabra, Barcelona. In the late 2021, he achieved one of the highly prestigious Marie Skłodowska-Curie Fellowship under the EUTOPIA-SIF programs for the years 2022–2023. His research interests include next-generation wireless local area networks (IEEE 802.11ax/ah/be), unlicensed wireless networks in 5G, the Internet of Things, performance evaluation of wireless networks, applied mathematics for wireless networks, reinforcement learning, and federated reinforcement learning techniques for wireless networks.

AMIR HAIDER received the B.S. degree in electronics engineering from the International Islamic University, Islamabad, Pakistan, in 2012, the M.S. degree in electrical engineering from the University of Engineering and Technology, Taxila, Pakistan, in 2014, and the Ph.D. degree from the Division of Electronics and Electrical Engineering, Dongguk University, Seoul, South Korea, in 2019. Before that, he has worked as a Lecturer with the Department of Electrical and Computer Engineering, COMSATS University Islamabad, Pakistan, from August 2014 to August 2015, and later from September 2019 to February 2020, after completing the Ph.D. degree. He was as a Postdoctoral Researcher at the School of Intelligent Mechatronics Engineering, Sejong University, Seoul, from March 2020 to February 2021. He is currently working as an Assistant Professor at the School of Intelligent Mechatronics Engineering, Sejong University. His research interests include URLLC for beyond 5G mobile networks, artificial intelligence aided wireless communication systems, MIMO antenna design, optical communication systems, and wireless positioning technologies.

HYUNG SEOK KIM (Member, IEEE) received the B.S. degree from the School of Electrical Engineering, Seoul National University, South Korea, in 1996, and the M.S. and Ph.D. degrees from the School of Electrical Engineering and Computer Engineering, Seoul National University, in 1998 and 2004, respectively. In 2003 and 2004, he held visiting researcher positions with the University of Virginia. From 2004 to 2006, he was with the Telecommunication Research and Development Center, Samsung Electronics. He is currently a Faculty Member with the Department of Information and Communication Engineering, Sejong University. His research interests include networking with special emphasis on wireless communication and visual light communication.

• • •