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Conceptualisation of Human-on-the-Loop Haptic Teleoperation With Fully Autonomous Self-Driving Vehicles in the Urban Environment

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ABSTRACT The automotive industry aims to deploy commercial level-5 fully autonomous self-driving vehicles (FA-SDVs) in a diverse range of benefit-driven concepts on city roads in the years to come. In all future visions of operating networks of FA-SDVs, humans are expected to intervene with some kind of remote supervisory role. Recent advances in cyber-physical systems (CPS) within the concept of Internet of Everything (IoE) using tactile Internet (TI) teleport us to teleoperate remote objects within the cyber-world. Human-on-the-loop (HOTL) haptic teleoperation with an extension of human control and sensing capability by coupling with artificial sensors and actuators with an increased sense of real-time driving in the remote vehicle can help overcome the challenging tasks when the new driver — artificial intelligence (AI) agent — encounters an unorthodox situation that can't be addressed by the autonomous capabilities. This paper analyses HOTL real-time haptic delay-sensitive teleoperation with FA-SDVs, in the aspects of human-vehicle teamwork by establishing two similar remote parallel worlds — real-world vehicle time-varying environment and cyber-world emulation of this environment, i.e., digital twins (DTs) — in which a human telesupervisor (HTS), as a biological agent, can be immersed with no cybersickness enabling omnipresence through a timely bidirectional flow of energy and information. The experiments conducted as a proof of concept of HOTL haptic teleoperation regarding learning with human-vehicle collaboration show promising results and the potential of benefiting from the proposed framework.

INDEX TERMS Autonomous vehicles, driverless vehicles, human-on-the-loop (HOTL), haptics, human-in-the-loop (HITL), human–vehicle coactivity, self-driving, tactile Internet, teleoperation, digital twins, Internet of Vehicles (IoVs).

I. INTRODUCTION

FULLY autonomous systems are human-out-of-the-loop systems that single-handedly determine the right course of action when given an autonomous task. They are currently making large impacts in a variety of applications involving robotics, ground vehicles and unmanned aerial vehicles (UAVs). Most of the vehicle manufacturers aim to deploy benefit-driven level-5 fully autonomous self-driving vehicles (FA-SDVs) in a diverse range of concept designs on city roads by leveraging extensive existing knowledge about sensors, actuators, integrated electronics and software components equipped with cognitive computing. All the big players in the automotive industry envisage a future for driverless vehicles and they have already taken notable actions within their manufacturing phases which are massively supported by leading technology companies (e.g., Samsung, Intel, Nvidia, Mobileye, Microsoft) [1]. The European Automobile Manufacturers' Association (ACEA), composed of 15 gigantic manufacturers, has placed "connected and automated driving" at the top of their priority list [2]. Those players are investing heavily in the technology and experimenting with autonomous technology and it's only a matter of time before someone releases the first commercially available SDV in the urban ecosystem [3].

Already autonomous car prototype models have covered millions of miles in test driving [3], most of the time with safety drivers as human-in-the-loop (HITL), i.e., hands-on. It is still unclear how long it will take to remove safety

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drivers from the loop for commercial SDVs. Deployment of SDVs without an in-vehicle human driver will be essential in scaling commercial FA-SDVs, not only from a conceptual point of view, but also from an economic point of view. Nissan believes the fastest way to get driverless cars on the road is to give them remote human support [4]. A framework is proposed in [5] to establish a high level of trust in FA-SDVs with no steering wheels and pedals. As an element of this framework, so-called "human-on-the-Loop (HOTL)" teleoperation is expected to establish a desired level of trust in FA-SDVs while they are interacting with a highly dynamic urban environment. In all future visions of operating networks of FA-SDVs, humans are expected to intervene with some kind of remote instantaneous supervisory role. We are on the verge of a transition into a fully connected networked society that will provide access to information and sharing of data anywhere and anytime for anyone and anything, hence, in the future wireless access will not only be about connectivity for people but for anything that benefits from being connected [6]. Recent advances in cyber-physical systems (CPS) within the concepts of Internet of Everything (IoE) and Automation of Everything (AoE) [7] using tactile Internet (TI) equipped with quality haptic feedback teleport us to teleoperate remote objects using digital twins (DTs), i.e., the virtual cyber-world embedded in the physical world. In this context, many companies testing FA-SDVs are developing remote operation capabilities, where a human in a control centre can take over and safely manoeuvre FA-SDVs in case of malfunctions or emergencies [8]. Location-independent remote real-time HOTL approaches using remote operators in a supervisory role are expected to speed up the removal of in-vehicle human drivers with increased trust in FA-SDVs.

As automation became more sophisticated, the nature of its interaction with a human has begun to change in profound ways beyond the traditional humans-are-better-at/machines-are-better-at (HABA/MABA) approach in which humans and machines are rivals and competing to grab the other's job [9]. The human-agent-robot teamwork (HART)-centric framework lets humans work with machines by leveraging their complementary strengths (i.e., augmentation) by promoting the collaboration between them for the development of profitable applications [10]. In this paper, the collaboration is analysed from the perspective of two intelligent self-reliant entities, skilled remote human driver and FA-SDV that are extremely dependent on one another for the successful management of rare difficulties within the HART-centric concept. In the rest of the paper, "human teleoperator" (i.e., master) and "in-vehicle teleoperator" (i.e., slave side) are titled as "human telesupervisor (HTS)" and "FA-SDV" respectively.

Despite their highly self-directed intelligent abilities, it would be unfair to expect SDVs to manage a highly unusual situation that even couldn't be handled by a skilled human driver. Remote teleoperation enables a skilled HTS to cooperate with an FA-SDV from a remote control centre in such scenarios wherein the new driver—artificial intelligence (AI) agent, is confused about what to do next while performing a task. Haptic HOTL teleoperation allowing precise emulation of the remote vehicle environment realistically can materialise appropriate location-independent manoeuvres wherever an intervention request is triggered either by the vehicle itself or the user in the vehicle. This paper addresses human-vehicle collaboration in delay-sensitive HOTL haptic teleoperation with FA-SDVs. More specifically, the crucial dynamics of decentralised HOTL teleoperation between the vehicle self-decision making abilities and remote human cognitive intelligence are investigated where teleoperated tasks are expected to be highly limited, learned and non-repetitive. To the best of the observed knowledge, this is the first comprehensive study that highlights a research gap in real-time HOTL teleoperation with FA-SDVs in the urban environment by considering TI equipped with haptics. While aiming to fill this gap, particular contributions in this paper are outlined as follows.

1) Effective telemanipulation of SDVs by democratising remote human driving skills in a harmonised human/autonomy ecosystem is analysed from technological, psychophysical and philosophical points of view.
2) By moulding the most contemporary techniques and approaches with a multiplicity of communication modalities using an orchestration of backhaul and fronthaul (i.e., crosshaul) mechanisms, a framework is developed to improve the efficacy of teleoperation.
3) The multi-agent vehicle learning and collaboration modes are explored from the perspective of two intelligent nodes — smart FA-SDV and skilled HTS — in a human-oriented and vehicle-centric approach by exploiting intelligence at the vehicle side.
4) The necessity and advantages of using the proposed framework are revealed within a proof-of-concept study that validates the efficacy of the framework regarding learning with human-vehicle collaboration.

The remainder of this paper is organised as follows. The related works are presented in Section II. The proposed methodology — HOTL-HT-SDV — is introduced in Section III. The multi-agent learning and collaboration modes in HOTL haptic teleoperation are explored in Section IV. Discussion is provided in Section V. Finally, Section VI concludes the key findings and outlines potential future directions.

II. RELATED WORKS

A multitude of state-of-the-art studies have been conducted on the human telemanipulation of robots since the first teleoperator was built in the mid-1940s by Geortz [11]. Teleoperation (i.e., telerobotics) interactions, particularly bilateral robotic teleoperation activities between humans and robots, have generally been analysed based on the master and slave concept in which the slave side is mapped as "teleoperator" and the master side is mapped as "human operator". Most of the studies in the literature focus on

HITL interactions usually based on the semi-autonomous mode for human and machine hybrid activities to accomplish assigned tasks together where semi-autonomous robotic systems are mainly designed with reliance on delay-tolerant human assistance. Within the same context, a deterministic teleoperation approach over an 802.11g wireless link within a narrow environment is proposed in [12] for semi-autonomous vehicle hazard avoidance and stability control. Suzuki *et al.* [13] analyse a HITL semi-autonomous vehicle teleoperation system using 3D maps and GPS time synchronisation in a highly deterministic environment. Dong and Chopra [14] propose a HITL tele-driving control design with a passivity-based adaptive control algorithm to enable a human driver to tele-drive a car-like mobile robot with haptic feedback using a two-degree-of-freedom (DOF) local robot (joystick). Zhang [15] discusses the vision, opportunities, and challenges in automated vehicle teleoperation. To the best of the observed knowledge, having received limited attention in the literature, teleoperating FA-SDVs in the urban environments has not been analysed in-depth in the sense of establishing a holistic HOTL approach involving haptics, which makes this paper unique aiming at closing this gap.

The real-world teleoperation initiatives with FA-SDVs are expanding within the industry. Today's teleoperation systems allow the interaction with environments at a distance and can also scale human force and motion to achieve stronger, bigger, or smaller action capabilities [16]. The automobile industry is partnering with leading telecommunication and technology companies that are experimenting with remote teleoperation of vehicles in stochastic environments. For instance, Phantom Auto,[1] Designated Driver[2] and Ottopia[3] propose remote control solutions for SDVs. Training of a Phantom's pilot takes about a week, starting with simulated driving, then teleoperation on a closed course before the driver passes a test to drive a car on public roads [17]. In late 2019, Alphabet's Waymo replaced some in-car human safety drivers with remote human operators for its robot taxi trials in Arizona, U.S. [15].[4] Nissan incorporated a degree of teleoperation into the autonomous car system, namely, seamless autonomous mobility platform, by which a human operator can remotely take control in unexpected situations via an LTE (Long Term Evolution) wireless connection where these FA-SDVs are capable of driving themselves most of the time [4]. However, 4G (fourth generation) technologies with a 20-25 milliseconds (ms) round-trip latency for an ideal environment cannot meet the stringent requirements of teleoperation in urban use cases from a risk point of view. Designated Driver works with a latency of around 100 ms using 4G [18]. Many individuals in the autonomous vehicle (AV) industry have theorised and convinced that teleoperation of vehicles is impractical because of their issues with latency — the inevitable delays that data packets experience as they wend their way from one end of a wireless connection to the other, and back again [17]. Therefore, vehicle teleoperation equipped with 5G/5GB (fifth generation/5G and beyond) technologies enabling both networking and computing with instant problem-solving mechanisms seems a viable solution to maintain trust in FA-SDVs during their real-world implementations.

Recently, 5G/5GB has been gaining momentum in teleoperating SDVs in the industry [15]. Major autonomous car players and many startups, together with the delivery industry and the telecom industry are developing vehicle teleoperation systems [15]. Samsung announced its remotely-controlled 5G car at the Goodwood Festival of Speed, with partners Designated Driver and Vodafone.[5] Vodafone's 5G network provides tremendously low latency with 10 times quicker than 4G. Baidu integrated 5G-enabled teleoperation into its vehicles to ensure public safety in extreme road conditions. All remote operators of Baidu complete more than 1,000 hours of cloud-based driving training without any accidents to improve the Quality of Experience (QoE) and to ensure the safety of users and pedestrians when the non-autonomous driving mode is engaged.[6] Drive.ai launches robot car pilot in Texas by keeping HITL [19] with remote interaction and intervention abilities (e.g., vehicle performance monitoring, stepping in emergencies). Ericsson and Einride, a Swedish electric-autonomous-vehicle company, built a test track in Sweden to see how remote operations would work in practice [20]. Einride provided the trucks, called T-pods, while Ericsson, in collaboration with Scandinavian telco Telia, supplied the 5G network. In ongoing trials, the T-pods are making deliveries between two warehouses in Sweden and a human has to take over by remote control in roughly 10% of the tests. These tests show that even though Einride trucks can drive themselves most of the time, it‘s best to have a person as HOTL for remote monitoring and control to easily step in when the new driver — AI — runs into an unorthodox situation.

Would the aforementioned approaches enable to take in-vehicle backup drivers out-of-the-loop? Could they provide an effective collaboration between HTSs and FA-SDVs in achieving tasks efficiently? They are mainly based on non-haptic audiovisual data without considering haptic physical interaction. However, human perception can be increased with a combination of audiovisual haptic information compared to using only one of them [21], the more multi-modal sensory information interacts with multiple human receptors, the better perception [22], [23]. In this regard, feeling the remote vehicle environment through a tight haptic physical coupling is crucial for the successful telemanipulation

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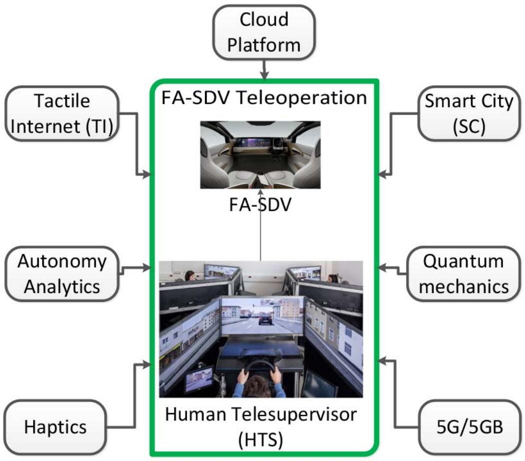

FIGURE 1. Main components of HOTL haptic teleoperation.[7]

of vehicles with better coherent human perception. On one hand, combined oriented complementary multi-modal sensory information, particularly, audiovisual information and fused state and situation awareness (SSA) information and another dimension, that is, haptic data can stimulate the multiple sensory receptors of an HTS to react swiftly. On the other hand, communication constraints lead to end-to-end (E2E) latencies and this destabilises teleoperation systems with FA-SDVs significantly, in particular, in the urban environments during peak hours with increasing traffic density and high velocities. TI has emerged in the last decade to communicate haptic and non-haptic information to location-independent nodes that are required to work collaboratively to achieve latency-sensitive tasks in real-time, which is elaborated in Section III-A along with other contemporary technological improvements that would contribute to the development of advanced teleoperation systems. To summarise, to the best of the observed knowledge, there is no in-depth study in HART-centric HOTL haptic teleoperation with FA-SDVs neither in literature nor in the industry for meeting the stringent requirements of vehicle teleoperation in the urban environments. Against this background, this paper is prepared to address this issue from technological, psychophysical and philosophical points of view by proposing a holistic framework.

III. METHODOLOGY

The essential components, outlined in Fig. 1, in tailoring the proposed framework — HOTL-HT-SDV — revealed in Section III-B are recapped in Section III-A.

A. BACKGROUND OF METHODOLOGY

1) VEHICLE AUTONOMY, HITL AND HOTL INTERVENTIONS

AVs have experienced a lot of upheavals since they were introduced with 5 levels of autonomy; the higher the level the more the autonomy for extended periods of time [1]. It is worth pointing out that level-4 and level-5 represent similar technology, but with a different concept where the aspects of level-5 — FA-SDVs — with no steering wheel, brakes, pedals, even not requiring a windshield and cockpit using an effective human-machine interface (HMI) put the manufacturer in a highly confident position [1].

HITL where the safety driver is supposed to be on alert all the time to fix any problem that the vehicle can not cope with is commonly used in controlling level-3 and level-4 autonomy. A level-5 autonomy is defined by the SAE J3016 standard as a system that can perform "under all driver-manageable on-road conditions" meaning that as perfect as a human driver. In this regard, this paper focuses on HOTL with FA-SDVs where the HTS is expected to intervene remotely in rare difficulties that the vehicle can not tackle under exceptional conditions.

2) HAPTICS AND TACTILE INTERNET (TI)

10.66 Peta-Bit/s has recently been transmitted over a single optical fibre [24]. Similar experimental studies have demonstrated that data transmission over 1 Peta-Bit/s per-fibre will be our daily routine soon in communication, in particular, using space-division multiplexing (SDM) rather than widely used wavelength-division multiplexing (WDM). Fibre-wireless (FiWi) access networks combine the reliability, robustness, and high capacity of optical fibre networks and the flexibility, ubiquity, and cost-effectiveness of wireless networks [25]. With the fascinating advancement of communication using the merge of backhaul and fronthaul (i.e., crosshaul), haptic rendering and TI enable remote haptic communications in teleoperating remote objects by delivering remote physical tactile experiences (i.e., delivery of skills) on an anywhere-anytime basis beyond the conventional content delivery perspective. Haptics, as an extension of visual and auditory modalities, refer to both kinaesthetic and tactile information and include position, velocity, force, torque, vibration, etc [26].

With the advent of commercially available haptic/tactile sensory and display devices, conventional triple-play (i.e., audio, video, and data) communications now extend to encompass the real-time exchange of haptic information (i.e., touch and actuation) for the remote control of physical and/or virtual objects through the Internet [27]. Furthermore, a lot of more novel, intelligent, user-friendly haptic devices are emerging with the advent of new functional materials, smart actuators and sensors, embedded computers, and the latest advances in real-time intelligence, machine learning, cognitive science, and AR/VR/mixed reality [28] leading to a better bilateral exchange of energy between two remote nodes. These advancements are highly supported by the standardisations of haptics on an application basis, e.g., IEEE P1918.1 [29].

A change in a haptic stimulus must exceed a certain level to become perceivable and this level, the minimal perceivable change, is referred to as the just noticeable difference (JND) based on Weber's law [30]. The importance and need

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[7] The image used for HTS is the courtesy of ©DLR.

of dynamic human haptic closed-loop behavior models and human perception models for the further improvement of haptic teleoperation systems regarding HITL is discussed for real-world problem domains in [16]. For high dynamic environments, a latency between 1 and 10 ms for the haptic channel is required [31]. For very high dynamic vehicle environments, 1 ms round-trip is a critical threshold in human perception of tactile response [32], [33]. The orientation of audiovisual information and haptic data is prime important not to cause a cybersickness. TI requires 1 ms of latency due to the nature of haptic signals and human perception [34] for achieving sensorimotor control over the communication channel [35], [36], by which the feeling of driving in the remote vehicle in a timely and realistic manner can be provided based on mechanical physics and psychophysics.

3) 5G/5GB, 6G AND USE CASES IN AUTONOMOUS VEHICLES

With 1 ms point-to-point (P2P) data transfer capability in 4G, the E2E round-trip latency is 20-25 ms for an ideal environment, which clearly indicates that 4G is not able to meet the stringent requirements of tactile response [32], [34]. On the other hand, with 0.1 ms P2P data transfer capability, 5G communication technology within a decentralised architecture enabling ultra-reliable and low-latency communication (URLLC) with i) enhanced mobile broadband (eMBB) focusing on high-resolution multimedia services, ii) massive machine-type communications (mMTC) focusing on IoT services enabling communication for a million devices/km^2, and iii) distributed computing abilities focusing on the accommodation of the ubiquitous implementation of applications within location-independent heterogeneous environments using software-defined networking (SDN) and virtual network function (VNF) (e.g., network function virtualisation (NFV)) where they are complementary one another is taking its indispensable place in IoE mobile applications, particularly in mobile teleoperation applications. Moreover, non-orthogonal multiple access (NOMA) is more popular than mMTC by maintaining the sleep and awake synchronisations (i.e., grant-free NOMA in uplink transmission and NOMA-MCD in downlink transmission), which can save the energy of the network along with reducing the latency and controlling signal overheads of the network [37]. The integration of generic services such as eMBB, mMTC, critical machine-type communication (cMTC), and URLLC can improve the performance of 5G-based applications; this service heterogeneity can be achieved by network slicing for an optimised resource allocation and an emerging technology, TI, to achieve low latency, high bandwidth, service availability, and E2E security [38]. Combined with SDN, NFV and edge computing, a new framework is developed in [39] to provide distributed and on-demand deployment of network functions, service guaranteed network slicing, flexible orchestration of network functions and optimal workload allocation.

Ultra-low-latency communication equipped with 5G is proposed for TI services in [31]. It is the key element of teleoperation with FA-SDVs and several studies [40], [41], [42] have achieved ultra-low latency with millimetre-wave (mm-WAVE) cellular networks in 5G cellular and next-generation wireless local area network (WLAN). This is achieved in the paper [40] using the medium access control (MAC) layer, congestion control, and core network (CN) architecture, in [41] using mm-WAVE-enabled massive multi-input multi-output (MIMO) networks and in [42] using properly aligned beamwidth antennas in mm-Wave.

Several approaches such as [43], [44] have been recently developed to make swarms of FA-SDVs safer and optimised on urban roads using the fusion of data from connected multiple SDVs, i.e., swarm intelligence using the understanding of connected and autonomous vehicles (CAVs) within the concept of Cooperative Intelligent Transportation System (C-ITS). The Release 16 (Rel-16) 5G New Radio (NR)-based C-vehicle-to-everything (C-V2X) technology brings new direct communication capabilities, such as high throughput and URLLC, for advanced autonomous driving use cases, while maintaining backward compatibility to Release 14 C-V2X; it provides 360° non-LOS (NLoS) awareness and extends a vehicle's ability to detect farther down the road, even at blind intersections or in poor weather conditions by sharing high-throughput sensor data along with their planned movements to each other [37].

While 5G technologies are taking their indispensable places in real-world implementations, it is worth mentioning that future 6G, at the expense of increased complexity, considers not only delivering another 1000x increase in data rates, but also diving into self-sustaining networks and dynamic resource utilisation; 6G will also put an end to smartphone-centric networks, introducing new system paradigms (e.g., HITL communications, human-centric services) [45].

4) QUANTUM MECHANICS

A rapid local fusion of computation-intensive multi-modal sensor data is of prime importance for rapid interaction between HTSs and FA-SDVs in teleoperation to meet the stringent requirement of 1 ms bidirectional close-loop interaction. Semiconductor technology made it easier to embed billions of micro-transistors or electronic mechanisms into a processor [7]. From this standpoint, transistors have truly revolutionised human existence by impacting practically everything in our everyday lives [46]. Transistors as small as atoms have led to quantum mechanics and quantum computing using qubits (i.e., $|0>, |1>$) has led to very powerful supercomputers that can harvest a tsunami of data volumes in nanoseconds using advanced analytics. Voluminous sensor data can be fused rapidly with extremely reduced time delays (i.e., with nanosecond delays) using onboard supercomputers equipped with quantum computing abilities, which reduces the data to be transferred significantly to the location of the HTS. Mimicking behaviors of quantum mechanics using entanglement has the potential in generating successfully bilateral synchronisation abilities in different distant locations.

5) SMART CITY, DIGITAL TWINS AND CLOUD PLATFORM

SCs by forging engineering and technology solutions with social dynamics in a new philosophical city automation concept - socio-technical transitions are being implemented to combine governors, organisations, institutions, citizens, environment, resources and assets and emerging technologies in a highly synergistic synchronised ecosystem to improve the quality of life and enable a more sustainable future for urban life [47]. FA-SDVs by executing non-trivial sequences of events with decimetre-level accuracy live in the urban environments and their integration with all the SC components and domains, in particular, intelligent transportation systems (ITS) using real-time data analytics is urgent to establish better swarm intelligent systems and a safer and optimised harmonious smart environment enabling cooperative FA-SDV-SC automation systems [1]. A specific E2E latency can not be exceeded in the teleoperation with FA-SDVs in the urban environments during peak hours with increasing traffic density to ensure the real-time required transparency, stability and performance. Extended by the cloud platform, SC by providing easy-to-use computing platforms and communication infrastructure equipped with 5G increases the efficient deployment of hand over wheels on robotised city roads with behavior coordination [1]. In this manner, construction of Digital Twins (DTs) that facilitate the means to monitor, understand and optimize the functions of all physical entities by i) pairing of the virtual and physical worlds [48], ii) enabling data to be seamlessly transmitted between the physical and virtual worlds [49] and iii) enabling the virtual entity to exist simultaneously with the physical entity [50] is an integral part of building healthy SCs, in particular, robust ITS within SCs. DTs integrate AI, software analytics, and machine learning data to create virtual models that update and change as their physical equivalents change [51]. In this context, a DT assisted real-time ITS for 5G-enabled Internet of vehicles (IoVs) enabling a real-time communication and data sharing interface between physical vehicles and virtual vehicles is proposed in [52]. The virtual DT of physical FA-SDVs within ITS as a cyber world dimension can improve HOTL haptic teleoperation significantly as elaborated in Sections III-B3 and IV.

UAVs are expected to be an important component of 5G/5GB cellular architectures that can potentially facilitate wireless broadcast or point-to-multipoint transmissions [53] where they can improve the bandwidth up to a much larger extent. Planning the future of SCs is discussed in [54] using an aerial-based MEC platform equipped with advanced leader fully autonomous UAVs (LFAUAVs) as shown in Fig. 2 for supporting coverage-constrained existing city network infrastructures. Technically speaking, LFAUAVs equipped with 5G/5GB communication abilities, intelligence data analytics capabilities and wireless power transfer (WPT) technologies is integrated with SC to meet the ultra-high reliability, ultra-high availability, and ultra-low latency requirements of SC applications using visual LoS (VLoS) links. UAV base stations (BSs) can detect the communication coverage holes [55] in the urban areas and position themselves [56], [57] appropriately to provide uninterrupted communication services over a city. In this direction, several LFAUAVs as the SC aerial MEC platform can close the coverage constraints in an urban environment with respect to the size of the city, which, in turn, help maintain the link reliability for mobile FA-SDVs. The wireless industry is already investing heavily in developing systems that operate in the mm-Wave bands, which are attractive because of the large quantities of available spectrum and the spatial degrees of freedom afforded by very high-dimensional antenna arrays (which are possible thanks to the smaller size of antenna elements at higher frequencies) [40]. In this context, small, light and high-gain smart antennas enable mm-Wave technology to be easily integrated with UAV systems, which promises new frontiers to be conquered in establishing effective and efficient future wireless networks such as 6G.

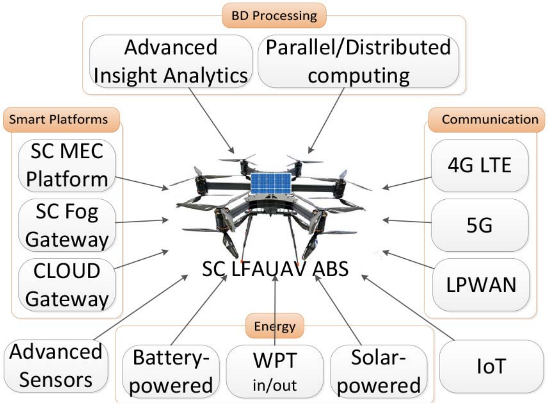

FIGURE 2. Main components of LFAUAVs.

B. HOTL-HT-SDV FRAMEWORK

HOTL haptic teleoperation with FA-SDVs requires real-time ultra-responsive bidirectional haptic interactions and seamless communications (e.g., appropriate actuation based on the audiovisual haptic data). Strictly speaking, the response of the HTS and the reaction of the vehicle along with its interaction with the environment must be synchronised with a high-quality emulation environment at the HTS side by facilitating haptic interaction with a high level of transparency, which aims to increase the HTS perception capabilities with a high level of QoE. The infrastructure — HOTL-HT-SDV — that enables a tight bidirectional physical coupling equipped with TI leading to a high level of transparency and stability between the HTS and vehicle is explored in Section III-B1. The management of E2E latency with ultra-high reliability, ultra-high availability, and ultra-low latency communication is explained in Section III-B2.

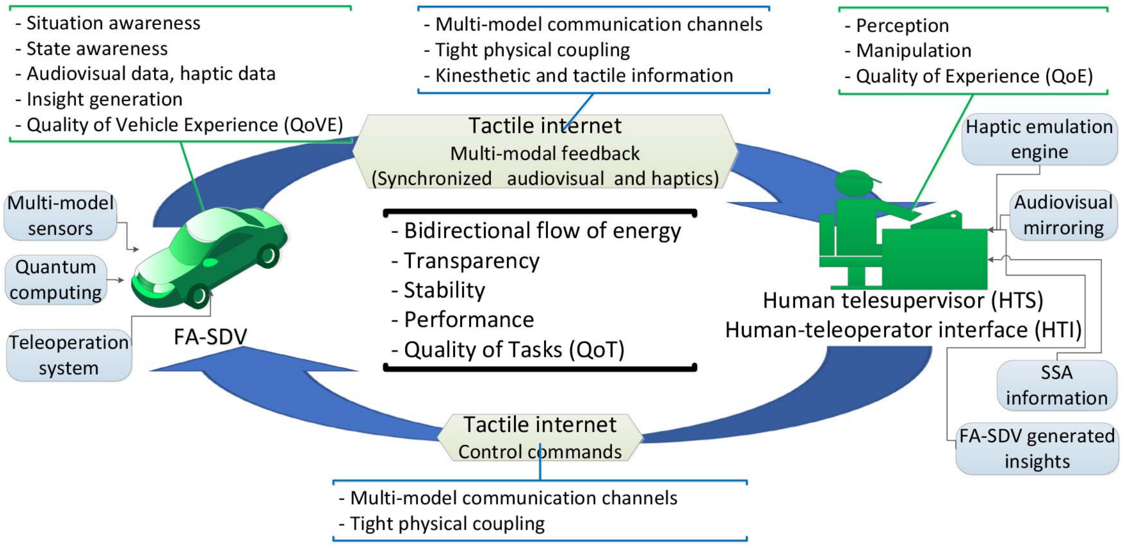

FIGURE 3. Elements of human haptic close-loop FA-SDV teleoperation.

The remote interaction between the two intelligent nodes — HTS and FA-SDV — with HOTL-HT-SDV is revealed in Section III-B3.

1) TOPOLOGY OF HOTL-HT-SDV

The essential elements of basic haptic teleoperation between HTSs and FA-SDVs are shown in Fig. 3 to address the aforementioned challenges in teleoperation. The haptic emulation engine, with appropriate haptic rendering abilities, allows the HTS to touch, feel, and manipulate FA-SDVs in complex urban driving environments. The integral components of the HOTL teleoperation using haptics can help i) render the vehicle‘s SSA data and sense of being in the vehicle and ii) communicate this digitised remote sense of the vehicle and its environment to the HTS. The main objective of using those components in a holistic system is to help the HTS to experience and perceive a realistic vehicle SSA leading to his/her appropriate and prompt decision-making in supervising the FA-SDV safely while realising its tasks optimally. However, communication delays highly affect both the closed-loop stability and performance of HTSs, often measured in terms of motion synchronisation and accurate rendering of the vehicle-environment interaction force to the operator [58]. The transfer of data requires massive communication bandwidth for reducing time-varying delays between two ends without causing cybersickness regarding the disorientation or desynchronisation of the inputs (e.g., audiovisual (real-time video compression), SSA and haptics). In order to mitigate these concerns, SC infrastructure initiatives have to enable the targeted ultra-high reliable, ultra-high available, and ultra-low latency human-to-everything (e.g., human-to-machine, human-to-robot, human-to-autonomy and human-to-vehicle) tactile interaction via haptic physical coupling beyond conventional machine-to-machine (M2M) communication. Within such an infrastructure, effective and efficient collaboration, cooperation and swarm intelligence can be fulfilled through instant human involvement with high QoE as HOTL to improve the urban ecosystem with high QoT. Within this context, an infrastructure — HOTL-HT-SDV — is outlined in Fig. 4 in which FiWi communications (i.e., broadband and mobile backhaul) using 5G NOMA and SC's very large bandwidth potential of optical fibre architecture are moulded with distributed MIMO concept to satisfy the E2E latency, reliability, and availability requirements of teleoperation.

There is now a growing awareness among industry players who extend the cloud with aims to decentralise the levels of self-managed entities; this trend toward decentralisation has led to the new paradigm of MEC, in which computing and storage resources — variously referred to as cloudlets —, micro datacentres, or fog nodes are placed at the Internet's edge in proximity to wireless mobile end devices in order to achieve low E2E latency, low jitter, and scalability [59]. Within 1 ms, light travels 300 km with a propagation delay, i.e., the maximum distance for a steering and control server to be placed from the point of tactile interaction by the users is 150 km away; however, this assumes no processing delays in the communication; taking the additional signal processing, protocol handling, and switching delays into account, this requires the control/steering server to be in the shorter ranges from the tactile point of interaction [60]. Within SC architecture, fine-grained haptic feedback and vehicle sensor fused data in teleoperation can be directed toward local data sites closer to HTSs and vehicles to guarantee a short response time rather than to a more centrally located site to meet the stringent low-latency and high-bandwidth requirements using SC facilities, e.g., SC fog platform, SC MEC platform, RSUs, edge devices. 5G needs to be a fully converged network, where multiple fixed and mobile access technologies can be flexibly selected sharing CN functionalities, leading to latency and reliability improvements [61]. The aforementioned architectural design supported by the

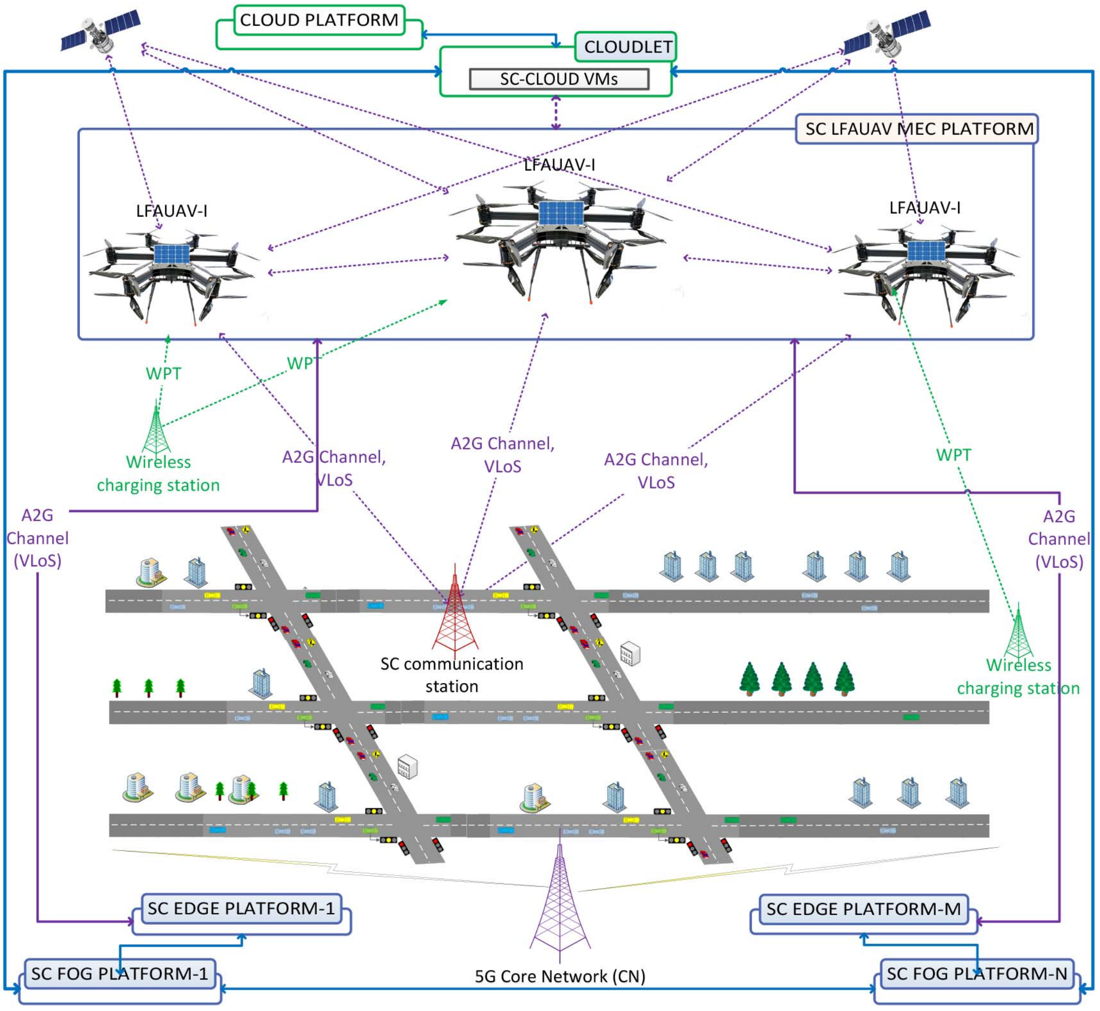

FIGURE 4. Topology of HOTL-HT-SDV using FiWi communications and distributed MIMO within SC.

SC network infrastructure provides a highly flexible sharing of resources in which the network resources are prioritised for teleoperation requests to guarantee the desired tactile latency. The deployment of integrated SC fibre infrastructure and 5G CN closer to urban roads would enable an efficient share of the CN functionalities and this would support massive mission-critical communications for ITS, in particular, latency-critical teleoperation with FA-SDVs. 5G-enabled TI reduces the E2E latency of the conventional techniques sufficiently and provides reliable and efficient AV applications [37]. More specifically, with large bandwidths, mm-Wave line-of-sight (LoS) MIMO technology employing parallel stream transmission is well suited for future wireless backhaul systems [62]. Moreover, NOMA-based access providing better latency with both downlink and uplink data transfer seems more advantages compared to mMTC in teleoperation.

With HOTL-HT-SDV, network resources are allocated dynamically to resource-intensive teleoperation networking requests and these allocated resources are orchestrated efficiently among the teleoperation collaboration requests using SDN with multiple simultaneous connectivity links. In this infrastructure, the urban communication coverage and bandwidth are supported by the SC aerial LFAUAV MEC platform (Fig. 2) as an aerial wireless backhaul on a 24/7 basis with a good coverage area for ultra-availability, ultra-reliability and ultra-latency requirements using LOS links within wide-area cellular networks by harnessing the abundant mm-Wave frequency spectrum. i) Two-way (air-to-ground/ground-to-air (A2G/G2A), downlink/uplink) P2P backhaul LOS connectivity, ii) distributed fog and edge datacenters with virtual machine (VM) synchronisation between HTSs and FA-SDVs, in particular using visible light communication (VLC) and iii) ultra-available multi-Gb/s mm-WAVE (frequency band: 30 to 300 GHz) with high data-rate transmissions abilities are crucial requirements in teleoperation where SDVs are in motion most of the time. These imperative links designed to achieve a high throughput using large bandwidth are redundant with multiple LFAUAVs as mobile relay nodes to ensure the ultra available requirement by coping with the synchronisation problem with distributed computation and storage abilities.

2) E2E LATENCY MANAGEMENT WITH HOTL-HT-SDV

The main challenge in HOTL haptic teleoperation with FA-SDVs is the establishment of ultra-responsive near real-time continuous communication in streaming a voluminous amount of sensor data. E2E packet delay or packet loss over time-delayed communication channels not only from a vehicle to an HTS, but also in the other direction destabilises the system due to the loss of instant contact with the vehicle environment that may result in unexpected manoeuvres (e.g., wrong trajectory, lane selection or velocity or acceleration/deceleration). Instability of a haptic communication system strongly deteriorates the immersiveness into the remote environment [63].

The haptic teleoperation elements between HTSs and FA-SDVs has to be synchronised robustly for creating a real-time DT of the physical environment to avoid any cybersickness. Immense advances in communication technologies can not solely provide the desired teleoperation capabilities. A flexible, reconfigurable and well-orchestrated crosshaul architecture needs to be tailored to meet the specific stringent requirements of teleoperation. This architecture has to allow several alternative highly prioritised mission-critical communication routes to stream packets using communication-as-a-service in a pay-as-you-go manner. In other words, not only do the packets need to be streamed using the joint design of efficient paths, but they also need to be streamed to the nodes closer to the changing vehicle locations, which requires a dynamic re-routing mechanism. To do this, an agent is generated for each FA-SDV teleoperation request and virtualised by NFV on the crosshaul network to manage the data traffic between two nodes — FA-SDV and HTS. The agent instantiates VMs at SC BSs or RSUs or virtualised BSs within 5G CN depending on the vehicle trajectory and HTS for caching. The ultra-responsive routing communication algorithm performed by the agent is presented in Algorithm 1 that ensures uninterrupted connectivity and synchronisation of data networking. Three threads, namely, i) very high priority network resource allocation, ii) streaming of packets from the vehicle to the HTS and finally iii) streaming of packets from the HTS to the vehicle run at a time in parallel for the orchestration of the streamed packets in a timely manner. This multithreaded algorithm is mainly designed to increase the efficacy of the human-vehicle collaboration modes that are elaborated in Section IV beyond the conventional master-slave approach.

Algorithm 1: Decentralised Network Resource Allocation With Routing Paths, Network Slicing and Streaming of SDV SSA, Audiovisual and Haptics Packets and HTS Actuation and Advisory Packets

```
Data: System input: Agent-ID & SDV-ID & HTS-IDs & SDV-Task &
        TO-Request & SSA-Packet-Size & Audiovisual-Packet-Size &
        Haptics-Packet-Size & Actuation-Packet-Size & SC-SDN-Paths
Data: Instant input: Channel-Quality-Report & SDV-CurrentLocation &
        SDV-ConnectionPoints & HTS-ConnectionPoints & SSA-Packets &
        Audiovisual-Packets & Haptics-Packets & Actuation-Packets
Result: Task-Completed & TO-Terminated
THREAD SPaths-SDN-NFV:
while TO-Request && NOT Task-Completed do
    =>Find the best paths, in particular, with LOS connection using SDN;
    [SDN-Mapped-Paths] = FindBestPaths[Channel-Quality-Report,
      SC-SDN-Paths, SDV-ConnectionPoints, HTS-ConnectionPoints];
    =>Network uninterrupted virtualised slicing for each component using
      each selected route using VNF;
    [SSA-Slices, Audiovisual-Slices, Haptics-Slices, Actuation-Slices] =
      NFV-Routing[SDN-Paths, SSA-Packet-Size, Audiovisual-Packet-Size,
      Haptics-Packet-Size, Actuation-Packet-Size];
    if FAGVCurrentDestination == FAGVDefaultDestination then
        =>The connection is establisphed;
        Connection-Established = True;
    else
        =>The connection is not establisphed;
        Connection-Established = False;
    end
end
THREAD SDV-STREAMING:
while TO-Request && Connection-Established && NOT Task-Completed do
    =>Each information components is streamed separately;
    => SSA streaming;
    SSA-Streaming[SDN-Paths, SSA-Slices, SSA-Packets];
    => Audiovisual streaming;
    Audiovisual-Streaming[SDN-Paths, Audiovisual-Slices,
      Audiovisual-Packets];
    => Haptics streaming;
    Haptics-Streaming[SDN-Paths, Haptics-Slices, Haptics-Packets];
end
THREAD HTS-STREAMING:
while TO-Request && Connection-Established && NOT Task-Completed &&
  HTS-Actuated do
    => HTS actuation streaming;
    Actuation-Streaming[SDN-Paths, Actuation-Slices, Actuation-Packets];
end
=>Either connection is lost or teleoperation request is ended;
if NOT TO-Request || NOT Connection-Established then
    if NOT TO-Request then
        =>The agent is terminated either by FA-SDV or HTS;
        =>All network resources released;
        Task-Completed = True;
        TO-Terminated = True;
        Connection-Established = False;
        EndNetworkResources[SDN-Paths, SSA-Slices, Audiovisual-Slices,
          Haptics-Slices, Actuation-Slices, AgentID];
    else
        =>Connection is lost; wait for the thread, SPaths-SDN-NFV;
        WAIT;
    end
else
end
```

- In the first thread, most efficient routing paths are determined with respect to the current locations of the two nodes and slicing within determined paths are allocated based on the packet sizes of multi-modal sensor components using SDN functions and virtualisation mechanisms with VNF for efficient virtualisation and management of network infrastructure (Section III-A3). Note that network slicing is performed on both wireless spectrum and CN resources to ensure the required reliability and availability. The slicing in wireless spectrum is managed dynamically whereas it is conducted in CN using the layers of Open Systems Interconnection networking (OSI) architecture. The communication reliability between the two nodes is achieved with a multipath routing design where the crosshaul network allows. The virtualisation of HTS commands wherever they are needed is highly important due to the changing trajectories of FA-SDVs where these commands have to follow. With

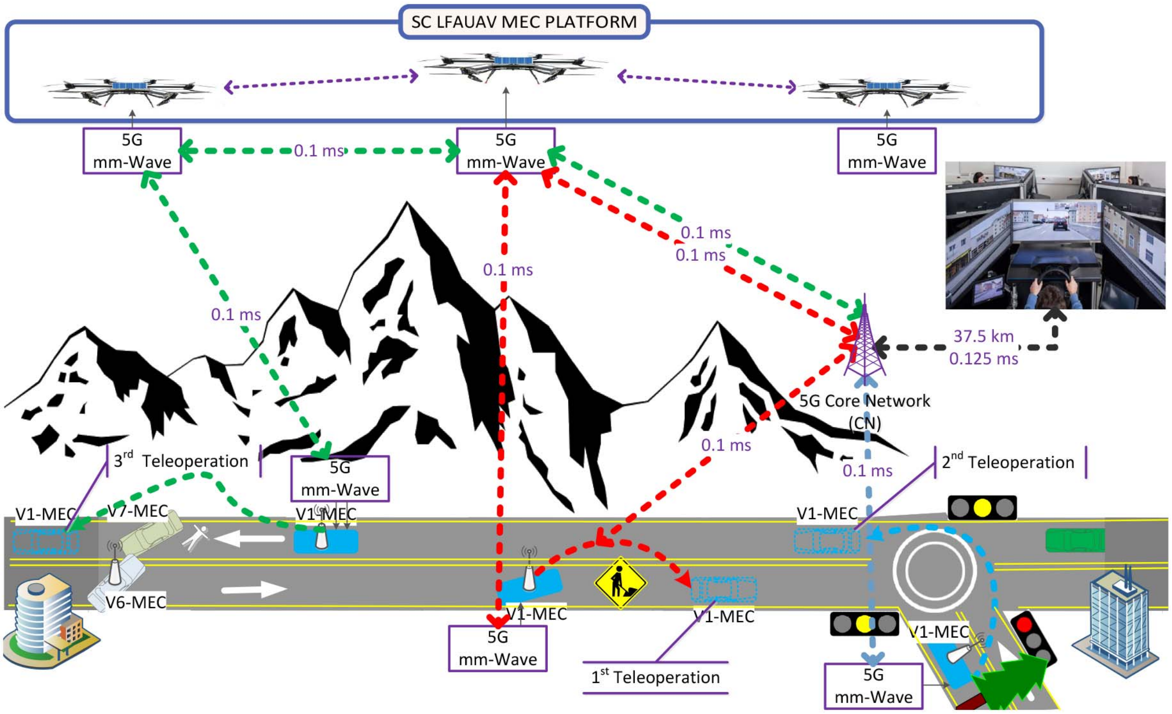

FIGURE 5. Multipath data streaming. Round-trip propagation latency during teleoperation: first half of 1st = 0.325 x 2 = 0.65 ms; second half of 1st = 0.225 x 2 = 0.45 ms; 2nd = 0.225 x 2 = 0.45 ms; 3rd = 0.425 x 2 = 0.850 ms.

most up-to-date channel quality reports and packet delivery statistics, SDN instantly figures out the most suitable paths with less-congested access points to deliver the packets efficiently. More specifically, three network slices in an optimal manner are allocated to the data components, namely, haptics, SSA information composed of the fusion of multi-modal sensors along with insights and audiovisual data where each slice is assigned to one of the components for streaming fragmented packets with high throughput. The size of instant haptic information may range from a few bytes to several megabytes depending on the multiplicity of the vehicle interaction with its environment and the size of SSA information along with insights may be several megabytes based on the resolution employed. However, the transmission of high-resolution audiovisual information requires large bandwidth for high data-rate transfer, which can be supported by multiple LOS mm-Wave links due to its large available bandwidth, in particular, provided by the LFAUAV capabilities (Fig. 2 in Section III-A5) with ultra-low latency, ultra-high reliability and ultra-high throughput on an anywhere-anytime basis using properly aligned antennas. The size of HTS commands will be no more than several bytes and transmission of them to the vehicle will be much faster than the communication in the other direction.

- In the second thread, mapping of data streaming to network functions is conducted by SDN in coordination with the agent through E2E orchestration. The data components (i.e., haptics, SSA and audiovisual packets) are streamed separately from the vehicle to the HTS through multiple available paths specified in the first thread.
- In the third thread, the commands of the HTS mapped to the allocated slice by SDN, again in coordination with the agent, are streamed to the vehicle using virtualised nodes based on the imminent locations of the vehicle as planned earlier in the first thread.
- In the last part of the algorithm, the deployed agent can be terminated either by the HTS or by the FA-SDV by ending the active HOTL teleoperation cooperation. Multiplexing of data streaming for each component is of high importance if one of the channels becomes unavailable due to any failure.

Telemanipulation with mobile FA-SDVs can not be restricted in a static operational environment. A reconfigurable system architecture based on the dynamics of both vehicle trajectory and current communication traffic is required to manage the real-time HOTL cooperation through dynamic seamless communication channels to secure continuous uninterrupted networking between two nodes. This dynamic structure is illustrated in Fig. 5. The data traffic is routed using different paths for the first and second half of the 1st teleoperation case where another path seems more efficient after a new LOS connection is captured with another available data communication node. The propagation latencies for three teleoperation cases are calculated concerning the locations of the vehicles and the current available resources. These latencies are within the targeted

1 ms round-trip. 0.35 ms and 0.55 ms in 1st teleoperation for the first half and second half respectively still remain for data processing; it is 0.55 ms and 0.15 ms in 2nd and 3rd cases respectively which are within sufficient timescale to meet overall 1 ms round-trip latency.

To sum up, within the proposed framework, E2E data traffic latency information is observed instantly using alternative communication channels composed of different routes via SC WLAN broadband and mobile backhaul. To this end, SSA and audiovisual data augmented with haptic data compressed by haptic codecs are transferred using these most available channels with the highest possible priority. This framework allowing faster access to multi-modal fused sensor data by HTSs, using ubiquitous simultaneous multiple connectivity links, in highly dynamic urban areas provides prompt mission-critical collaboration between HTSs and FA-SDVs through a tight haptic physical coupling over well-established communication channels. Furthermore, the ubiquitous simultaneous multiple connectivity links within this architecture make simultaneous data transmission/receiving highly reliable with no packet loss, in particular, the use of different channels for the audiovisual and haptic packets streams, which, in turn, can fix any connection failures rapidly where delays in haptic data transmission can undermine the stability of teleoperation. The separate data elements transferred to the HTS cyberworld at a time with ultra-low latency E2E paths have to be synchronised properly via a scheduling protocol to remove any cybersickness for HTSs in making FA-SDVs physically tangible. More specifically, the proper synchronisation and integration of SSA, audiovisual and haptic data using recalibration processes with the correspondence parametric cues is imperative for reducing discrepancies/mismatches leading to a high level of transparency, which is elaborated in Section III-B3.

3) TELEOPERATION WITHIN HOTL-HT-SDV

Confidence in the telemanipulation of FA-SDVs can be increased with the seamless transparency between two remote locations. Within stable and consistent transparency, HTSs can feel the remote vehicle environment realistically with a high level of perception through effective haptic interaction with efficient bidirectional flow of energy and information over a tight physical coupling between two nodes. In plain English, success in a vehicle teleoperation system lies in human haptic/audiovisual perceptual limits with high QoE affected by the computational performance, the quality of fused multi-modal sensory data and networking delays. As mentioned earlier, E2E communication delays should be reduced to sub-ms for proper 1 ms round-trip time-critical interactions involving the processing of acquired sensor data. Offloading this data over a remote centre (e.g., the cloud or fog platforms) for processing (to be fused for ultra-low latency requirements) can not be tolerated to meet this targeted latency. Thereby, local processing of high voluminous data in FA-SDVs using in-vehicle built-in MEC platform equipped with quantum mechanics allowing intensive computational capabilities paves the way for transforming instant voluminous multi-modal sensor data into fused abstract forms and insights readily (i.e., 0.1 ms) — information, knowledge and wisdom — which decreases overall latency and traffic load over the backhaul (e.g., CN) substantially by avoiding unnecessary data traffic [64].

Teleoperation systems have to be designed in a human-oriented manner to increase QoE in supporting human decision-making capabilities and they have to provide effective intervention interfaces in the best possible way in a machine-oriented manner for improving QoT. The components of an E2E teleoperation design with a high level of transparency, stability and performance via instant haptic interaction are presented in Fig. 6. This architecture enabling URLLC leverages both wireless 5G/5GB and SC wired backhaul technologies aiming at a tight remote engagement of HTSs with vehicles and their environments. Onboard multiple cellular modems enable redundancy of the communication links with a broader coverage area to ensure the transfer of fused information augmented with audiovisual data using multiple channels, in particular, with the SC aerial MEC platform. This platform supports multiple wireless networks simultaneously and wide-area connectivity throughout the urban area with A2G VLOS ubiquitous and flexible links with a highly offloading efficiency as elaborated in Section III-B1.

The teleoperation data traffic is categorised as "emergency" on a priority-based routing scheme within SC-based crosshaul communication. With HOTL haptic teleoperation, HTSs with telesensing, teleactuating and computer-aided supervisory control abilities can manipulate FA-SDVs remotely through a human-vehicle interface fed by the instant fused sensor data on a location-independent basis. The remote teleoperator mounted on the FA-SDV performs the command signals stimulated by the HTS; the generated haptic feedback signals with the vehicle are sent back to the HTS within a close-control loop where each action affects the next state of the vehicle within a continuous motion; the next state determines the ensuing manipulation actions. More specifically, i) the sensors perceive remote contact with the real-world in various physical forms; haptic and audio-visual signals are captured by the teleoperator; the multi-modal data is fused by the built-in vehicle quantum computing abilities to result in abstract insights (i.e., information, knowledge and wisdom) (e.g., best trajectory options) iii) the remote contact sensation information (i.e., haptic and audio-visual signals) along with those insights involving the local vehicle SSA are transmitted into the cyber-world wherein the remote contact information is processed by the haptic interface to generate similar distortion/reaction force/feeling, iv) the actuation generated by the haptic interface reproduces the haptic sense perceivable by the HTS in a well synchronised and orchestrated manner with other observed audiovisual information and v) the HTS closes the loop of haptic feedback using the manipulation mechanisms with a highly stable control loop interaction in the other direction. The interaction

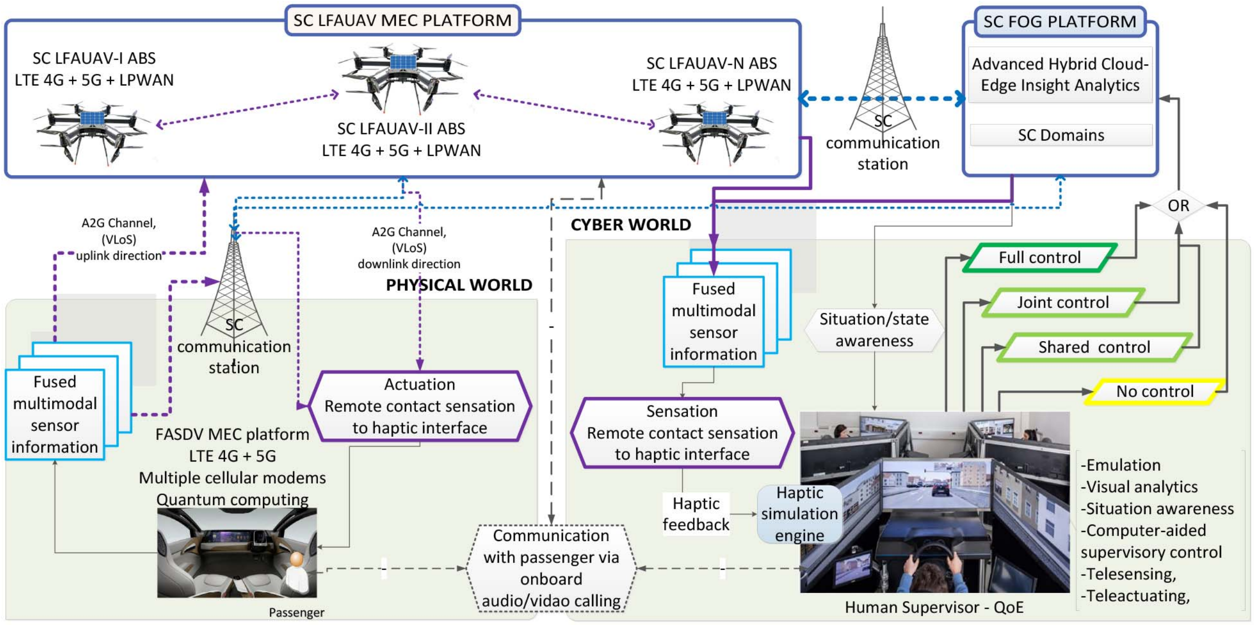

FIGURE 6. E2E HOTL haptic teleoperation with prioritised P2P hybrid wireless and wired networking. A tight physical coupling between the HTS and FA-SDV by establishing two similar remote parallel worlds (i.e., digital twins) — real-vehicle-world (left) and its cyber-emulation-world (right).

phases within various collaboration modes are elaborated in Section IV, in particular, from a cognitive perspective.

A remotely operated vehicle under poor communication conditions with poor SSA information may lead to high failure rates, even fatal accidents. The biggest challenge in the non-fault-tolerant and non-delay-tolerant HOTL teleoperation with FA-SDVs is the instant intervention requirement with a high level of perception without significant time delays (e.g., action and reaction speed). An HTS centre with an interface with less cognitive load can facilitate easy-to-use functions compatible with real-world vehicle abilities. State-of-the-art safety-critical interface functions with advanced infrastructures equipped with ground-breaking communication abilities with proper timing and advanced analytical tools need to be reinvented using appropriate haptic technologies to provide proper coupling and time-critical interactions between the cyber-world of HTSs and the physical world of FA-SDVs. These software-in-the-loop and hardware-in-the-loop interfaces can be excelled using multidisciplinary approaches involving anthropology and sociology to combine the physics of vehicle mobility, its instant SSA information and the human perception properly in line with the human cognition abilities. Bilateral haptic rendering, i.e., digitisation of the remote sense, enabling true interaction within the cyber-world by perceiving the remote environment simultaneously while interacting is promising for quick and proper human response by stimulating more human sensing abilities. Haptic stimuli to an HTS can be generated to convey continuous information about the real-time environmental interactions by increasing the sense of being in the remote vehicle enabling instant response. For instance, a haptic simulation of a collision with a vehicle in the real world can be emulated into a form by which the HTS can perceive this collision by a haptic simulation engine. Haptic transducers can convert haptic signals into a combined form that is perceivable by the HTS realistically. More concretely, audible vibration can be generated using appropriate vibration transducers (e.g., vibromechanical actuators) to grab the HTS‘s attention; motion effect can be created with computed interaction forces; the sound of the collision can be produced using audio transducers with audio rendering. Similar instant tactile (i.e., surface texture pressure/friction sensation to skin using mechanoreceptors) and/or kinesthetic (e.g., velocity, acceleration, position, road bumps, force, torque, vibration sensation (i.e., vibrotactile stimuli) to hand, wrist, muscles, joints, limbs, tendons) feedback along with audiovisual feedback can stimulate the HTS with joint forces. Hardware-in-the-loop kinesthetic devices can allow the HTS to take quick and proper action, such as applying time-critical pressure on the brake to decelerate or manoeuvre appropriately in another way. Thus, the HTS can be immersed into the remote FA-SDV real-world by seeing, hearing and most importantly by feeling the remote physical environment. To reduce the teleoperation requests and make FA-SDVs completely self-sufficient in the long run, analytics enabling collaborative learning needs to be integrated with teleoperation systems. With this in mind, multi-agent learning with regards to collaboration modes between the HTS and vehicle are explored in Section IV.

As an emerging promising infrastructure, mobile cloud computing (MCC) equipped with cloudlets, integrated FiWi access networks, 5G technologies, and decentralised mobile MEC platforms is expected to alleviate the shortcomings of resource-limited mobile nodes significantly, e.g., high-computation and low-latency requirements. Location-independent FA-SDV teleoperation from one city to another or anywhere in the world can be performed via resource-rich MCC offloading by closing a global control loop with a global communication within the limitations of the communication technologies where very long-distance E2E communication is susceptible to high propagation latency (e.g., the propagation delay of light in optical communication as elaborated in Section III-B1).

IV. MULTI-AGENT LEARNING WITHIN HOTL-HT-SDV AND COLLABORATION MODES

An FA-SDV may confront a wide range of unusual scenarios in partially observable, multiagent, stochastic, sequential, dynamic, and continuous urban environments.[8] HTSs and FA-SDVs need to collaborate and cooperate to achieve various tasks in this highly unpredicted urban roads. Joint activity between humans and robots takes place in a mutually experienced situation, in which all parties' experience provides the basis for how plans, actions, and their expected outcomes are individually understood [66]. Proper communication plays a crucial role in building up a shared form of situational awareness to aid coordination and collaboration [66]. Time-varying delays are inevitable during teleoperation regarding the communication time delay problem, decision-making delays regarding QoE of HTSs and the evaluation of the voluminous sensor data and actuation time delays. Moreover, human remote intervention is vulnerable to human decision errors regarding incomplete environmental information based on the current state and imminent states of the vehicle with respect to other traffic participants, obstacles and hazards. Even with a high level of SSA information, HOTL teleoperation is strictly dependant on the cognitive and perceptual capabilities, spatial orientation abilities and motor skills of HTSs to avoid risky manoeuvres. FA-SDVs as being in an advantageous position have instant local SSA. To avoid any unexpected disastrous result, effective collaboration can be established by exploiting the autonomous mode self-decision making abilities of FA-SDVs and the cognitive intelligence of HTSs. HTSs and FA-SDVs can work together closely to i) increase the efficacy of decision-making, ii) establish tasks optimally and safely and iii) remedy any probable decisions with errors.

As specified in Section III-A1, this paper focuses on HOTL with FA-SDVs where HTSs are expected to intervene in rare difficulties that the vehicle can not tackle using their decision-making abilities. In other words, constant human intervention for FA-SDVs is not desirable. Rare intervention requests are expected to be triggered where an impending hazard or predicament is not copped with by autonomy. The one-to-one task assignment requires a sufficient number of HTSs regarding the number of vehicle collaboration requests. The number of HTSs concerning one-to-one associations may be large during the initial penetration of FA-SDVs where one HTS can manage only one vehicle effectively at a time. This number can be reduced by classifying the urgency of intervention requests as "highly urgent", "urgent" or "not urgent". An HTS must be assigned to a vehicle for a "highly urgent" request where "urgent" and "not urgent" requests are prioritised in a queue to be assigned to the next available HTSs if all HTSs are in active mode. Vehicles with "urgent" or "not urgent" intervention requests are expected to pull over to the side of the road with activated emergency flashers where their move is risky or these vehicles, by taking themselves in a safe mode, reduces their speed and manoeuvres until an HTS is assigned. Vehicles with "highly urgent" intervention requests are expected to force themselves to pull up in a safe position if their move is highly risky and there is no available HTSs. Most importantly, the number of HTSs can be reduced where the intervention requests are decreased as FA-SDVs adapt to the urban environment using incremental event-based adaptive automation by replacing human participation through collaborative learning. Teleoperation with FA-SDVs is not only the remote manipulation of them for solving a problem, but also building up their knowledge for being independent in the long run by taking the human-out-of-the-loop where the concept of an FA-SDV is not only removing the in-vehicle human backup driver, but also removal of any remote human intervention involving an HTS.

A. MULTI-AGENT LEARNING WITHIN HOTL-HT-SDV

The knowledge (e.g., unique problem-solving ability) and skills of HTSs need to be transmitted to swarms of FA-SDVs for realising these main objectives. Human interventions aim to improve the self-decision-making abilities of FA-SDVs and FA-SDVs are expected to take proper behaviors themselves without requesting human intervention using the learned attitudes by mimicking the behaviors generated by HTSs alone or collaboratively wherever similar conditions are confronted. In this direction, event-based adaptive automation through the replacement of human participation through collaborative learning is illustrated in Fig. 7. This concept can be conceptualised using Eq. (1), shown at the bottom of the page. In this abstract formulation, constant automation learning with a multi-agent learning mechanism is performed through an aggregation of a large number of vehicle agents' experiences

$$\begin{aligned} &HOTL = SDV - 1 => CondA => HOTL - request => Problem - solved => Next - cond => All - SDVs - trained \\ &NoHOTL = SDV - ANY => CondA => Learned - behaviour - triggered => Behaviour - implemented => Next - cond \end{aligned} \tag{1}$$

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[8] Readers are referred to [65] for the detailed definitions of these terms.

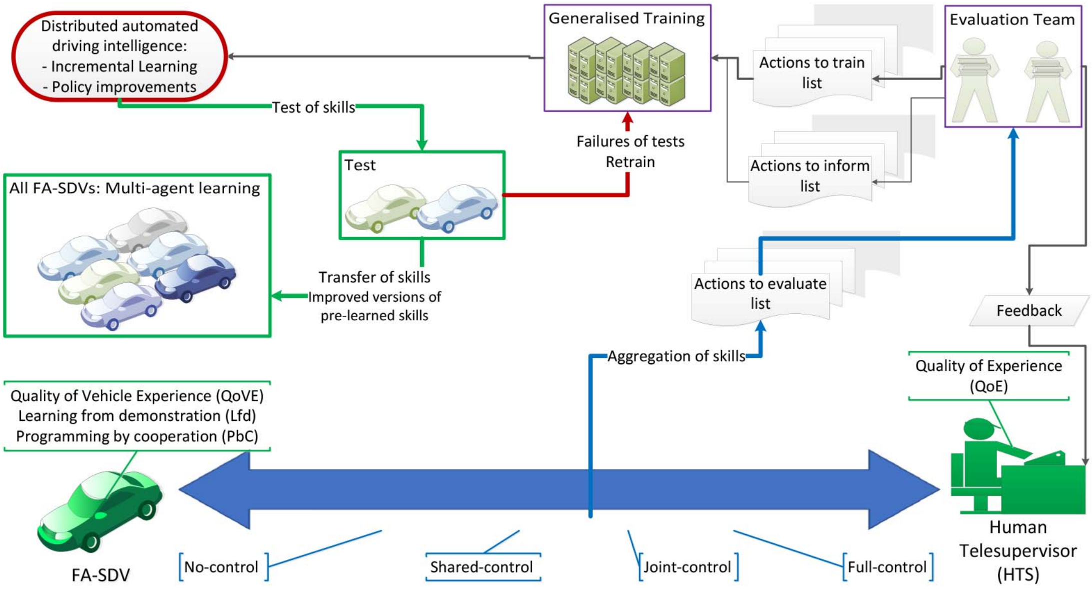

FIGURE 7. Multi-agent event-based adaptive automation: replacement of human participation through collaborative learning.

with multi-FA-SDV and multi-HTS engagement using various collaboration modes (Fig. 8). For better training and vehicle learning of multiple complex tasks, a number of HTS demonstrations for particular fine-granular tasks are required for a high level of task abstraction to reduce variability in the QoE of HTSs. In this regard, the aggregation of cooperation and collaboration instances from multiple HTSs is of prime importance in combining the experiences/skills into the most sensible generalised fine-tuned learning outcomes.

Multisensorial SSA information along with audiovisual and haptic data during the collaboration is recorded to establish generalised training files for generating mathematically represented policy functions in which respective states and following actions are defined $((P_1 = s_n, a_n, s_{n+1}, a_{n+1} \ldots) \cdots (P_k = s_n, a_n, s_{n+1}, a_{n+1} \ldots))$. Complex situations are mapped to actions within these state/action-driven policies, in particular stochastic policies rather than deterministic policies in a highly unpredictable uncertain urban environment. "Evaluation team" composed of multidisciplinary experts involving legislators, psychologists, sociologists determine the actions to be trained for all other FA-SDVs to increase QoVE and feed HTSs with constructive feedback for improving their QoE in the sense of reducing variability to reach the desired level of QoE. The use cases placed in the "actions to train" list by filtering suboptimal HTS manipulations are collaboratively trained and shared among FA-SDVs. This learning process can be highly productive if the aforementioned phases are carried out in a global manner involving all FA-SDV service providers. Based on the established policies, FA-SDVs determine convenient policies regarding their current states, SSA information and their objectives and then execute a course of actions/transitions (i.e., state-action — $s_n, a_n, s_{n+1} \ldots$) within the determined policies without needing human telemanipulation. It is worth noting that an action phase (i.e., a_n) may be associated with a series of parallel or sequential sub-actions with respect to the time where a state may require to trigger more sub-actions (e.g., steering left and deceleration at a time and then acceleration again ($a_n = \{T_1 : a_{n_1}, a_{n_2}; T_2{:}a_{n_3}; \cdots)\}$). This is mainly required to achieve tasks optimally with required physical positioning using desired joint torques and forces in the current complex state and then to reach the next state in an advantages position where consecutive states are strictly dependent on the preceding states.

Learning is the acquisition of knowledge, skills, or abilities through experience [67]. Deep Reinforcement Learning (DRL) using passive and active learning in addition to Gaussian Mixture Models (GMMs), Recurrent Neural Networks (RNN) (e.g., continuous-time RNN), Hidden Markov Models (HMM), and Convolutional Neural Networks (CNNs) has improved significantly in the last decade to make behaviour learning and collaborative learning easier and faster [64]. Interactive/collaboration learning in a virtual environment supported by augmented reality reduces the time, labour, and cost [68]. Despite these huge improvements in AI, still, intelligent agents have highly limited abilities in cognitive learning when compared to a human. Within this context, learning with supervisory interaction is highly useful where there are no prior datasets and it may not be feasible to establish sufficient training. The environment may be changing dynamically and it might be difficult to predict this dynamic environment at the start completely, which requires learning through executing tasks with interactions. Collaborative learning during interaction using cognitive computing can help FA-SDVs to learn during the collaboration modes of the HOTL teleoperation instantly. In this direction, **Learning from Demonstration**

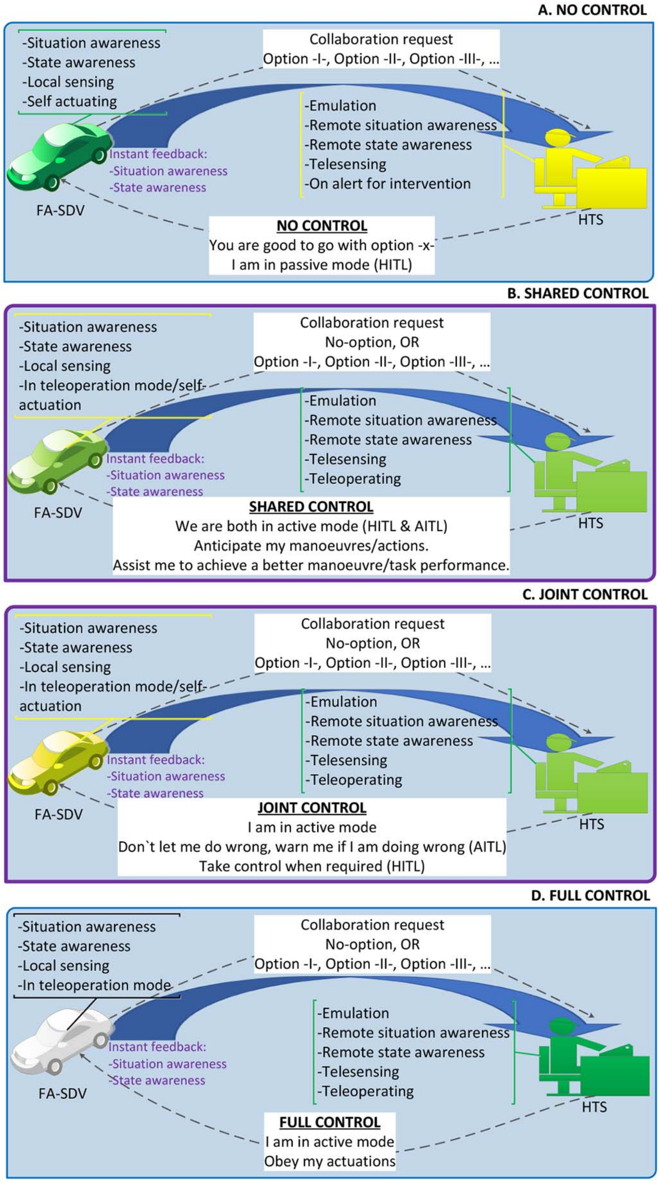

FIGURE 8. **Collaboration modes of HOTL haptic teleoperation with a high level of transparency.**

(LfD) [69] (i.e., Programming by Demonstration (PbD) [68]) lets intelligent agents acquire new skills to imitate a skilled human without needing to be programmed by engineers, i.e., by facilitating non-expert agent programming. On the other hand, **Programming by Cooperation (PbC)** [68] focuses on making intelligent agents learn tasks from humans by interacting and cooperating with them. The main reason for choosing LfD and PbC over other agent learning methods is that ideal behaviour can be neither scripted (as is done in traditional robot programming) nor easily defined as optimising a known reward function (as is done in reinforcement learning), but can be demonstrated [69]. FA-SDVs learn how to cope with the difficulties through HOTL haptic teleoperation collaborations in the long run as formulated in Eq. (1), which would make them more self-sufficient with less human intervention.

The collaboration responsibilities, liabilities and intentions during telemanipulation have to be identified to make the aforementioned behavioral learning properly based on agreed-upon standards. The two intelligent nodes have to learn how to cooperate with one another in a predictable way to establish a task optimally. An FA-SDV goes into the teleoperation mode by triggering a collaboration request from an HTS if it runs into a confusing situation. The HTS i) may not need to take over control or ii) partially takes control where the vehicle anticipates the HTS' interventions and assists in achieving the desired task smoothly within the concept of human-vehicle shared control, or iii) takes control where the vehicle may not yield the actions taken by the HTS within the concept of human-vehicle joint control or iv) fully takes control of all vehicle manoeuvres. These HOTL collaboration modes are illustrated in Fig. 8 as "no-control", "shared-control", "joint-control" and "full-control". These modes designed for specifying the responsibilities and liabilities and what to pursue during probable cooperation conflicts between two intelligent entities— HTS in a human-oriented and FA-SDV in a vehicle-centric approach — by exploiting intelligence at the vehicle side and cognitive capabilities at the human side can be summarised as follows.

B. COLLABORATION MODES WITHIN HOTL-HT-SDV

No-control mode (Fig. 8 A) in which the involvement of HTSs is minimised: the HTS as a task-specific HITL encourages the FA-SDV in a non-decisive mood to take either one of the options (Ex: V4 (red) in Fig. 9) determined by the vehicle itself or a different predetermined option. The HTS may act in a further supervisory role and alternatively, any instant suggested trajectory with various waypoints drawn on a screen that views the vehicle's SSA information can be instructed based on the characteristics of the task and SSA to help the FA-SDV to navigate appropriately to tackle the difficult situation confronted. The HTS as a potential teammate monitors the vehicle as HITL while the suggested action is being implemented without any human element. S/he remains as a supervisor but is on high alert either for new guidance or for taking control of the vehicle if not happy with the way of the implementation/navigation. The implemented option is learned to be performed next time with the same situation by the vehicle with their highly adaptive nature without notifying the HTS. Moreover, this implemented option is sent to all other FA-SDVs (Ex: V5 in Fig. 9) approaching the same location in order not to trigger a collaboration request, which aims to both reduce the workload of the HTS and increase the mobility in the short term. In a test environment of Nissan, an incident, a construction obstacle in the way, took 90 seconds to resolve using the teleoperation manipulation, but the results were also transmitted to a second autonomous vehicle close behind; coming across the same obstacle and receiving the same instructions, the second car was delayed by only 12 seconds [4]. Furthermore, this implemented option is placed in the "actions to evaluate"

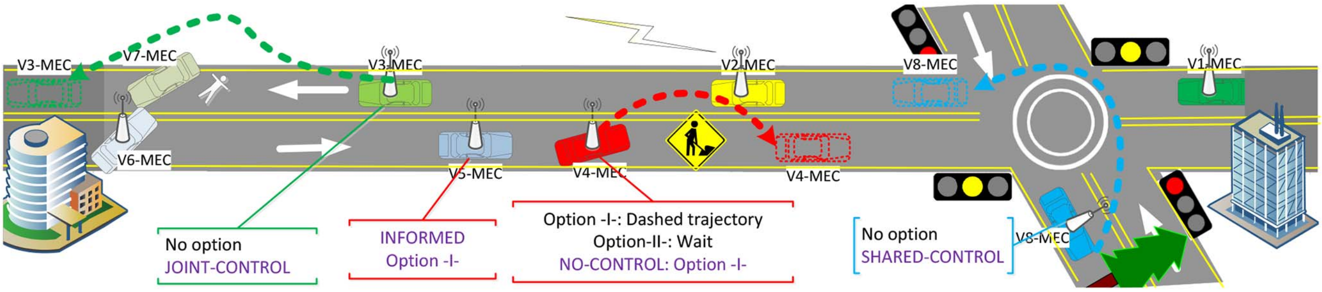

FIGURE 9. Examples for collaboration modes.

list to be examined by experts. The actions in the "actions to evaluate" list are transferred into the "actions to train" list to be learned by all other FA-SDVs if determined as imperative to train all FA-SDVs. The required training files are established for the items in the "actions to train" list to train all other vehicles, which aims to improve the self-decision-making abilities of all FA-SDVs, in the long run, to make them more self-dependent and self-sufficient equipped with highly improved AI-based MEC capabilities through minimised human collaboration as illustrated in Fig. 7.

Shared-control mode (Fig. 8 B) in which a simultaneous synergistic tighter togetherness is required within a mutual concurrent coactive interaction: some tasks may not be achieved by allocating sub-task responsibilities distinctively between the HTS and FD-SDV, which requires tight shared teamwork to achieve a satisfactory task with acceptable task performance. Furthermore, the HTS may not reproduce the identical manipulation of the vehicle when performing the same task again (especially for the complex tasks that the vehicle was already in difficulty to cope with) even with the same haptic/audiovisual input with respect to the changing human phycological selective perception affected from QoE, mental/psychological state, characteristics, attention levels, tiredness, new environmental factors etc. The manipulation sometimes might be similar, but not identical leading to the achievement of the task; sometimes may result in total failure, e.g., leading to fatal accidents. Volatile QoE may affect QoT dramatically and quantisation of a vehicle teleoperation system may not be easy based on the agreed-upon performance metrics. To overcome similar discrepancies in the system, in the shared-control mode, neither the HTS is in full control of the FA-SDV nor the FA-SDV is in full control of itself; they work together collaboratively requiring continuous and tight interaction to execute complex tasks or critical exceptional manoeuvres out of the agreed-upon norms in the urban dynamic traffic environment (Ex: V8 (blue) in Fig. 9).

The HTS leads the FA-SDV with no option or adequate options appropriately. The FA-SDV, by knowing the main task (determined either by the HTS or by the FA-SDV itself), anticipates imminent manoeuvres of the HTS and assists him/her proactively to perform them smoothly and efficiently. The trajectory specified by the HTS can be diverted slightly and appropriately by the vehicle to drive around an obstacle with no need to inform the HTS. The objective in this mode is to achieve tasks efficiently and safely using a socio-cognitive model leading to synergistic task performance. Vehicle built-in safety mechanisms (e.g., collision avoidance) remain operational all the time. As explained above, the "actions to evaluate" and "actions to train" lists are conducted similarly in this mode as illustrated in Fig. 7. The PbC technique is performed for training. In this mode, a full collaboration between the HTS and FA-SDV is expected to accomplish a high-quality task or tackle the current difficulty confronted. It is worth asking several questions in this mode to direct the researchers into a fruitful research area: can tasks be achieved in identical ways in the shared mode when repeated? How does an established level of confidence in an FA-SDV affect the performance of an HTS positively and negatively? Does too much confidence in an FA-SDV result in complacency leading to a reduction of the efficacy of the togetherness? Can a reduction in the performance of an HTS be compensated by an FA-SDV? How does the change of one's task performance influence the other's performance? How can competing commands be integrated for a high-quality task experience?

Joint-control mode (Fig. 8 C) in which allocated/assigned series of fine-grained sub-tasks within a task are performed individually: neither the HTS is in full control of the FA-SDV nor the FA-SDV is in full control of itself where various specific sub-tasks are allocated between the HTS and FA-SDV beforehand. The control is traded back and forth to execute fine-granular sub-tasks. It is worth mentioning that all upcoming situations (e.g., sub-tasks) while realising a task can not be foreseen in a highly complex urban mixed traffic in advance. In this sense, the HTS leads the FA-SDV with no option or no adequate options (Ex: V3 (green) in Fig. 9). The HTS may need to take control for a period of time for better task performance. Different from the no-control mode, this time, the FA-SDV is on high alert as autonomy-in-the-loop (AITL) to intervene by harnessing its SSA advantageous position where vehicle built-in safety mechanisms (e.g., collision avoidance) remain operational all the time to avoid any hazard. The FA-SDV may not comply with the actions performed by the HTS if they are determined as inappropriate by the FA-SDV based on the local SSA information

TABLE 1. Main distinctive features of the collaboration modes.

Modes	Loop	Learning	Decision	Obedience FA-SDV	Obedience HTS	Solution for conflicts	Full control	Built-in safety mechanism
No-control	HITL	Rule-based	HTS	Yes	No	N/A	Yes (SDV)	Operational
Shared-control	HITL & AITL	PbC	HTS & SDV	No	Yes	HTS & SDV	No	Operational
Joint-control	HITL or AITL	LfD	HTS	No	No	HTS	Partial	Operational
Full-control	N/A	LfD	HTS	Yes	No	N/A	Yes (HTS)	Inactive

(e.g., collision detection). This non-compliant attitude with the reason (e.g., the light is red!!! I am supposed to stop) is sent to the HTS. The HTS i) takes another action by yielding the request or ii) may relinquish control to the vehicle or iii) may insist on the same action. The FA-SDV tends to perform the same action if it is insisted where responsibilities and liabilities lie with the HTS. The HTS passes control back to the vehicle for the tasks to be executed by the vehicle or may leave the control to the FA-SDV for executing the instant emerging sub-tasks. The HTS is on alert all the time as a sub-task-specific HITL to take control at any time while the FA-SDV is executing its allocated sub-tasks. The collaboration is carried out under the authority of the HTS. As explained above, the "actions to evaluate" and "actions to train" lists are conducted similarly as illustrated in Fig. 7. The LfD technique is implemented for training.

Full-control mode (Fig. 8 D) in which all sub-tasks in a task are performed by the HTS: the HTS takes control and leads the FA-SDV with no option or no adequate options. Different from the joint-control mode, the FA-SDV, piloted remotely by the HTS, obeys the manoeuvres performed by the HTS under any circumstances. This mode is not harnessing the local intelligence of the FA-SDV requiring substantial input from the HTS. The mode might be selected because of the failures of i) several imperative onboard sensors causing a weakness in SSA and/or ii) main actuators used for essential manoeuvres. The use of this mode could be a catastrophe and employment of this mode requires strict regulations and standardisations such as limitations in velocity and manoeuvres; it should not be selected during peak hours with high-density traffic. In this mode, the HTS is expected to obtain the SSA information using SC facilities if there is any problem in acquiring this information from the vehicle. The HTS can pull up the vehicle somewhere safe as a last resort if the imperative sensors or actuators are seriously damaged. The LfD technique is implemented for training if the vehicle is functioning with a sufficient quality level of SSA.

The main distinctive features of the collaboration modes are summarised in Table 1 and their moderate examples are illustrated in Fig. 9. It is worth emphasising that no-control mode should be encouraged by the HTS as a guide operator if the FA-SDV has at least one reasonable option to perform itself. It is expected that the option can be performed better by the vehicle without any human intervention since it is already learned by the vehicle. In other words, it is a time where the AI can empirically be proved to be on such a high degree of superiority that the human's input may affect the task performance negatively. If there is no predetermined option, the HTS can exploit the onboard intelligence with either the joint-control mode or shared-control mode within the concept of master-master beyond the conventional master-slave interaction. In this respect, the joint-control and shared-control modes with no full control over to HTSs or FA-SDVs by taking full advantage of the autonomous capabilities of FA-SDVs are expected to be employed most of the time rather than the full control mode that may cause disastrous consequences. In these two modes, both nodes assist one another in the decision-making process through coordinated actions for achieving a task optimally, safely and synergistically. Most importantly, the vehicle may override the directives of the HTS to some extent to avoid any hazard. The vehicle can take necessary safe actions itself using the self-driving ability where the connection is lost with the HTS. Combining human and robot skills via intelligent interfaces seems very appealing; in this manner, establishing principled shared control methods to seamlessly blend the control between the human and the robot to enable the combined system to surpass both the robot and human performance with reduced human effort is a prime goal for robotics [70]. The full control mode has to be employed in very limited conditions as specified above, in particular, where the joint-control and shared-control modes can not be applicable, e.g., SSA problems.

A merge of these collaboration modes can be employed by switching from one mode to the other for specific parts of a complicated task to cope with highly difficult challenges. In such circumstances, how to decide to switch to another mode (and switch back as well) and how and when to implement the switch, especially with a high-speed vehicle may be the main concerns that need to be addressed. As mentioned earlier, FA-SDVs, having instant SSA (e.g., vehicle health, vehicle state and its semantic understanding of the environment involving other traffic participants, a rich representation of the location, vehicle's immediate surroundings (road bumps, other vehicles), spatial information, vehicle's position, acceleration), would be in an advantageous position with an initiative to determine the implementation of the switching decisions agreed by the two intelligent nodes using their autonomous capabilities. However, switching decisions between modes can be determined based on the characteristics and dominance of the modes as presented in Table 2. For instance, the switching decision for "from no-control to shared-control and then to joint-control and then to full-control and then again back to no-control" is controlled and carried out by SDV, HTS, HTS and 'HTS & SDV together' respectively.

TABLE 2. Node control responsibilities for the switching.

Switching decision	Current control	Next control	Current dominance	Next dominance	Switching control
No>shared	SDV	SDV-HTS	SDV	SDV&HTS	SDV
No>joint	SDV	SDV-HTS	SDV	HTS	SDV&HTS
No>full	SDV	SDV-HTS	SDV	HTS	SDV&HTS
Shared>joint	SDV-HTS	SDV-HTS	SDV&HTS	HTS	HTS
Shared>full	SDV-HTS	SDV-HTS	SDV&HTS	HTS	HTS
Shared>no	SDV-HTS	SDV	SDV&HTS	SDV	SDV
Joint>full	SDV-HTS	SDV-HTS	HTS	HTS	HTS
Joint>no	SDV-HTS	SDV	HTS	SDV	HTS&SDV
Joint>shared	SDV-HTS	SDV-HTS	HTS	SDV&HTS	HTS
Full>no	SDV-HTS	SDV	HTS	SDV	HTS&SDV
Full>shared	SDV-HTS	SDV-HTS	HTS	SDV&HTS	HTS
Full>joint	SDV-HTS	SDV-HTS	HTS	HTS	HTS

QoE in TI measures the difference between the experience with physical interaction and remote operation [71]. Performance differences between the actions executed by an in-vehicle driver and an HTS can be measured to quantify the QoT and the performance of the teleoperation system while they are executing the same tasks. These measurements that would help confirm the expected performance can be utilised i) for specifying the acceptable performance differences regarding the tolerable levels and ii) for reducing performance differences with improved QoE and iii) for increasing the quality of the overall teleoperation system leading to improved QoT. The less the difference, the better the overall teleoperation system based on the accepted gold standard or ground truth, in-vehicle drivers, using agreed-upon benchmarks. Furthermore, training files for various specific tasks can be generated by in-vehicle drivers to train all other FA-SDVs. With this in mind, the standardisation of teleoperation collaboration would be beneficial to manage the interactions between two intelligent entities in a highly synchronised environment. Mixed-critical cost-effective and timely interactions with HOTL teleoperation systems can enable FA-SDVs to cope with many uncertainties instantaneously, in particular, those created by varying human driving patterns in mixed traffic. This will increase and maintain trust in FA-SDVs, which, in turn, speeds up the penetration of these smart vehicles into mixed traffic.

C. PROOF OF CONCEPT

It is assumed that i) the penetration of FA-SDVs into mixed traffic is %1 increase each day starting with 100 vehicles up to a maximum number of 150,000, ii) each SDV demands 5 teleoperation requests from HTSs to fix their unique unorthodox situations, iii) each HTS can work 4 hours each day and each teleoperation request takes 10 min, and iv) the starting number of HTSs is 21 where 5000 min = 100 SDVs * 5 times * 10 min and 21 HTSs = 5000 min / 240 min.

The required number of HTSs increases dramatically where the number of SDV increases each day (%1) without learning as depicted in Figure 10. Strictly speaking, it becomes 31,250 when the maximum penetration number (i.e., 150,000 with 750,000 teleoperation requests) is realised on the penetration day, 736, and this is neither feasible regarding the management nor economical. On the other hand, using 0.01 learning rate, (i.e., %1 of teleoperation request is reduced by learning each day (Fig. 11)), it becomes 19, 2 less than the starting point, i.e., 21, as displayed in Figure 12 where the average teleoperation request per SDV diminishes to 0.003096 from 5. On the penetration day, 1031, all SDVs become completely self-dependent with needing no teleoperation via learning. It is worth noting that the workload in the learning phase doesn't increase where the daily real learning rate that indicates the learning difference from the preceding day decreases each day as shown in Figure 11 (blue line). The rate should not be rising in order not to grow the staff number in the training phase (Figure 7) where its increase requires more effort. It can be adjusted by the learning rate (i.e., 0.01) chosen at the start of the simulation based on the penetration rate of SDVs.

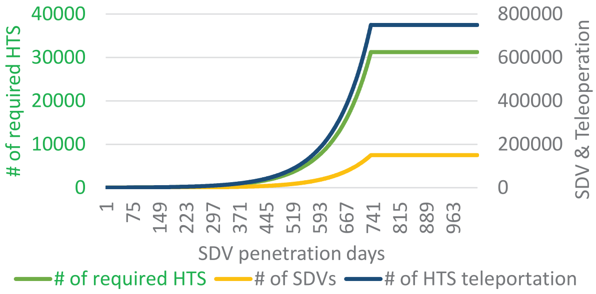

FIGURE 10. The number of HTSs with no learning (bottom).

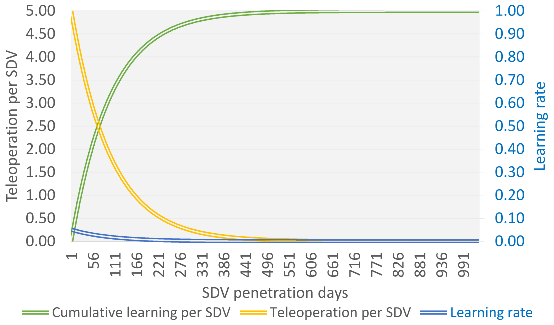

FIGURE 11. Reduction of teleoperation per SDV with learning.

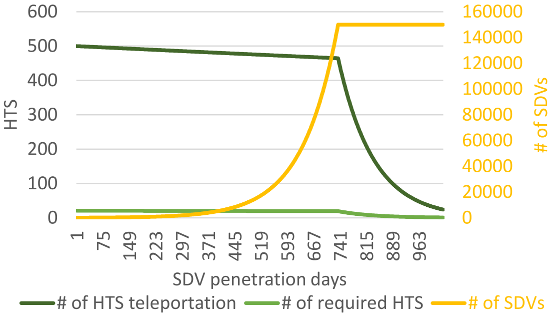

FIGURE 12. The number of HTSs with learning.

V. DISCUSSION

While FA-SDVs are already experimentally deployed, they, by mimicking the human cognition for eliminating HITL, will become ubiquitous in the years to come in the urban environments. Will humanity forget how to drive in the future? Despite the current challenges in autonomous driving, this technology will likely become ubiquitous soon [72]. It is boldly envisioned that by 2040, all vehicles will be completely driverless, and it might even be illegal for humans to drive on public roads in a new traffic ecosystem in which all vehicles are centrally controlled [73]. FA-SDVs with a variety of significant societal benefits will gradually dominate the transportation market [74]. It is of prime importance to fix any unexpected problem remotely with instant problem-solving mechanisms using vehicle teleoperation (i.e., remote driving) within the concept of HOTL as a rare human intervention by considering public safety and remote nonnegligible cybersecurity threats. What makes the HOTL concept a reasonable intervention in FA-SDVs is that despite decades of prior research and a renewed interest from technology companies and the research community, many gaps remain in the capabilities of AVs [75], in particular, performing evolutionary cognitive learning in the event of uncertain conditions. Therefore, remote problem-solving abilities should be incorporated into FA-SDVs during their design and development phases. A learning mechanism elaborated in Section IV-B is highly important not only to make the system manageable, but also to materialise the main objective of SDVs that is self-dependant by taking the human-out-of-the-loop requiring even no teleoperation.

TI is the future advancement of the current IoT vision wherein haptics, or touch and senses, can be communicated from one geographical place to another, enabling near real-time control and navigation of remote objects [76]. The transparency of the current teleoperation systems with SDVs is far from perfect with many unresolved issues, in particular, the transmission of real-world haptic impedance, leading to poor task performance. Haptic input assists teleoperators to work in a near real-world transparent environment that almost provides a similar task performance as in manual manipulation based on the numerous research and tests performed on haptics [77], [78]. To this end, lagging in developing an effective HOTL teleoperation with FA-SDV by which an HTS can align himself/herself properly to take over control of vehicles on a location-independent basis will slow down the removal of in-vehicle human backup drivers (the replacement of HITL with full autonomy), which in turn, becomes the main drawback in scaling commercial FA-SDVs, in particular, from an economic point of view. Until FA-SDVs become completely self-dependent with expedited vehicle self-learning capabilities, HOTL abilities with the tight engagement of remote skilled HTSs through taking one course of optimal action over other less optimal or disastrous actions by maximising the expected utility can maintain trust in this technology. The intelligent agents that can learn by mimicking HTSs without requiring expert programming are envisioned to dominate AI applications to make them self-sufficient requiring no HITL and HOTL. It is also envisioned in [1] and [5] that the number of HTSs will diminish significantly as the penetration level of FA-SDVs increases where FA-SDVs can solve most of the difficulties using mMTC and cMTC between themselves with the concept of "connected and automated driving" without needing frequent human intervention.

The mobile Internet with low-latency and high bandwidth capabilities enabling access to information on an anywhere-anytime basis has democratised our life in many aspects, in particular, providing fast remote operation abilities. TI will become a driver for economic growth and innovation and will help bring a new level of sophistication to societies [60] within the concept of TI of Things (TIoT) with the improving haptic feedback, e.g., smell sensors, smart gloves or even suits that can be invisibly planted into the fabric of the environment. It is envisioned that 5G/5GB and 6G communication technologies can redefine the automotive industry by offering high communication speed for immersive user experiences, as well as new infotainment, telematics, and teleoperation use cases [37]. With the rapid development in the areas of multimedia hardware and with the emergence of TI technology, traditional media systems can be evolved into collaborative, interactive, and immersive multimodal systems [32]. In this direction, telemanipulation is evolving from a content-oriented concept to a skill-deliverable-oriented concept. By democratising the remote driving skills with novel immersive experiences, location-independent HOTL haptic teleoperation using TI equipped with 5G/5GB and 6G will be one of the critical real-time human-vehicle automation utilities in remote controlling of FA-SDVs. Haptics will be immensely employed at the forefront of telemanipulation. Advanced human-vehicle interaction (HVI) interfaces enriched with advanced haptics are required to teleoperate FA-SDVs optimally and safely. Besides, imminent manoeuvres within teleoperation collaboration modes should be communicated to the other traffic participants around the vehicle either using onboard visual cues or using C-ITS to increase the efficacy of teleoperation. 6G enabling more extensive coverage with high capacity and low latency anytime everywhere will boost the development of TI applications and near-real-time teleoperation systems with FA-SDVs.

Many studies envision a future with FA-SDVs with increasing penetration levels in mixed traffic. However, effective management of FA-SDVs in real-world use cases under highly uncertain conditions has not been examined sufficiently in the literature. The proposed framework in this paper, HOTL-HT-SDV, focuses on how to facilitate an effective and efficient telecooperation between HTSs and FA-SDVs by generating a virtual real-world representation of FA-SDVs, i.e., DT. It exploits the self-decision making abilities of the vehicle autonomous mode and the cognitive intelligence of the HTS where time-varying delays are inevitable in telemanipulation. HOTL-HT-SDV can achieve an ultra low latency, enabling HTSs to manipulate FA-SDVs at higher speeds through rapid action-state-reaction mechanisms. This research could be applied to wider real-world applications in line with the commercial design and development of SDVs while TI and 5G/6G communication technologies become dominant within SCs.

VI. CONCLUSION AND FUTURE DIRECTIONS

Sometime in the future, humans may forget how to drive physically, but need to learn very well how to teleoperate FA-SDVs with location-independent remote control abilities using V2X technologies equipped with haptics and TI to easily step in when the new driver — AI — encounters an unexpected situation that can't be handled by the autonomous capabilities. To close the literature gap in this field, in this paper, an in-depth discussion is provided in building an ecosystem that aims to establish a common ground for an ideal location-independent collaboration between skilled HTSs and intelligent FA-SDVs. Within a conceptual holistic framework titled HOTL-HT-SDV, HOTL haptic teleoperation with FA-SDVs using two similar remote parallel worlds — real-world vehicle environment and cyber-world emulation of this environment, i.e., DTs — is investigated from technological, psychophysical and philosophical points of view. HOTL haptic manipulation with critical, cost-effective and timely interventions, by enabling omnipresence, can be instrumental in empowering FA-SDVs to cope with many uncertainties instantaneously. Reaping the full benefits of this framework can speed up the penetration of these vehicles into mixed traffic with a high level of trust without the need to wait for this technology to be perfect; that is a point almost impossible to reach. Besides, coactivity aspects of two intelligent entities — HTS and FA-SDV — are examined in this paper by addressing how to improve the QoT while tasks are operated collaboratively in the sense that the high QoT can be achieved through a tight bidirectional interaction with the high QoE and QoVE. Contrary to the HABA/MABA approaches in which humans and machines are competing to grab the other's job, the proposed conceptual HART-centric framework, though promoting effective human involvement is mainly designed to make FA-SDVs completely self-directed by taking the human-out-of-the-loop. Human participation requisites are replaced with adaptive automation through robust collaborative/behaviour learning. The conducted proof of concept demonstrates the potential of benefiting from learning within collaboration modes.

This study is expected to encourage further improvements on haptic devices that pave the way for an effective HOTL haptic teleoperation with FA-SDVs in reducing the mismatches between the real-world vehicle time-varying environment and cyber-world emulation of this environment. The synchronisation of multi-modal data transmitted via different channels for removing cybersickness will be a focus following this paper. Further research on how a vehicle can improve its QoVE from the actions performed by humans or collaboratively using cognitive learning by intuitively emulating real-world behaviors with no expert directions is imperative to unlock the full potential of FA-SDVs. How to teleoperate multiple FA-SDVs beyond one-to-one association will be another fruitful research direction towards this discipline.

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