Technical Report: Analysis of Intervention Modes in Human-In-The-Loop (HITL) Teleoperation With Autonomous Ground Vehicle Systems

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Abstract

Vehicles are becoming increasingly automated by taking on more and more tasks under improving intelligent control systems equipped with enhancing sensor technologies and Artificial Intelligence (AI) techniques from the prior automation level to the next automation level – targeting full autonomy. Fully autonomous systems are human-out-of-the-loop systems that single-handedly determine the right course of action when given an autonomous task. In all future visions of operating networks of fully autonomous self-driving ground or aerial vehicles, humans are expected to intervene with some kind of remote instantaneous intervention role and ``Human-on-the-Loop (HOTL)'' and ``Human-in-the-Loop (HOTL)'' telemonitoring and telemanipulation is expected to establish a desired level of trust in AVs while they are interacting with a highly dynamic urban or aerial environment. Many studies envision a future with fully autonomous self-driving vehicles (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. This report, by covering the teleoperation collaboration modes between two intelligent agents — human telesupervisors (HTSs) and FA-SDVs — aims to close this gap.

Keywords: Autonomous vehicles, driverless vehicles, human-on-the-loop (HOTL), human-in-the-loop (HITL), human–vehicle coactivity, self-driving, digital twins.

1. INTRODUCTION

Vehicles are becoming increasingly automated by taking on more and more tasks under improving intelligent control systems equipped with enhancing sensor technologies and Artificial Intelligence (AI) techniques from the prior automation level to the next automation level – targeting full autonomy [1]. Fully autonomous systems are human-out-of-the-loop systems that single-handedly determine the right course of action when given an autonomous task [2]. 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 [2]. In all future visions of operating networks of fully autonomous vehicles (AVs), humans are expected to intervene with some kind of remote supervisory role [3]. What makes the Human-In-The-Loop (HOTL) concept a reasonable intervention in AVs 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 [4]. Recent advances in cyber-physical systems (CPS) within the concepts of Internet of Everything (IoE) and Automation of Everything (AoE) [5] teleport us to teleoperate remote objects using digital twins (DTs), i.e., the virtual cyber-world embedded in the physical world [6]. HITL 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 — AI agent — encounters an unorthodox situation that can't be addressed by the autonomous capabilities [7]. Digital Twins, DTs, i.e., the virtual cyber-world embedded in the physical world, help map the real-time dynamic features of physical assets to the virtual world in multidimensional space [8] to interact with physical assets and change their states [9]. This report analyses HITL real-time delay-sensitive teleoperation intervention modes with FA-SDVs, in the aspects of human-vehicle teamwork using 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 enabling omnipresence through a timely bidirectional flow of information. Location-independent remote real-time HITL 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 [10].

2. COLLABORATION MODES IN TELEOPERATION BETWEEN HUMANS AND 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 [11]. 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 [12]. In this report, the collaboration is analysed from the perspective of two intelligent self-reliant entities, a 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 report, "human teleoperator" (i.e., master) and "in-vehicle teleoperator" (i.e., slave side) are titled "human telesupervisor (HTS)" and "FA-SDV" respectively. Collaboration modes should take the self-decision-making abilities of the vehicle's autonomous mode and the cognitive intelligence of the HTS into consideration where time-varying delays are inevitable in telemanipulation.

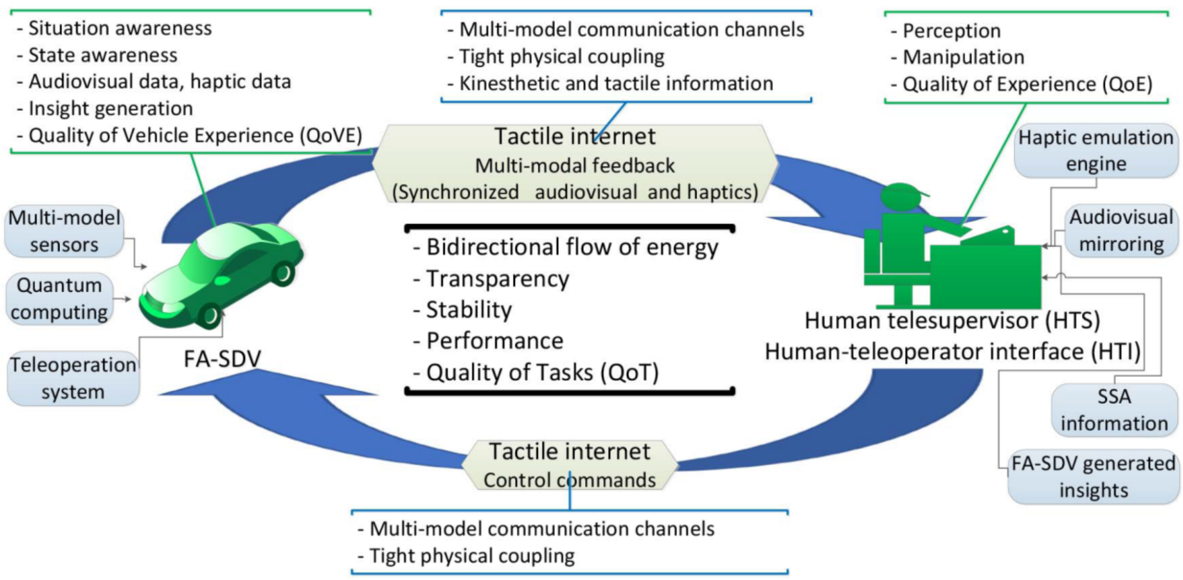

Figure 1: Elements of human haptic close-loop FA-SDV teleoperation.

The essential elements of basic haptic teleoperation between HTSs and FA-SDVs are shown in Fig. 1 to address the 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 HITL teleoperation using haptics can help i) render the vehicle‘s state and situation awareness (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. The two intelligent nodes have to learn how to cooperate in a predictable way to establish a task optimally. An FA-SDV goes into 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 HITL collaboration modes are illustrated in Fig. 2 as "no-control", "shared-control", "joint-control" and "full-control". These modes designed to specify 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.

No-control mode (Fig. 2 A): 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 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 in the same situation by the vehicle with its highly adaptive nature without notifying the HTS.

Shared-control mode (Fig. 2 B): 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 Quality of Experience (QoE) may affect the Quality of Task (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. 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 sociocognitive model leading to synergistic task performance. Vehicle built-in safety mechanisms (e.g., collision avoidance) remain operational all the time.

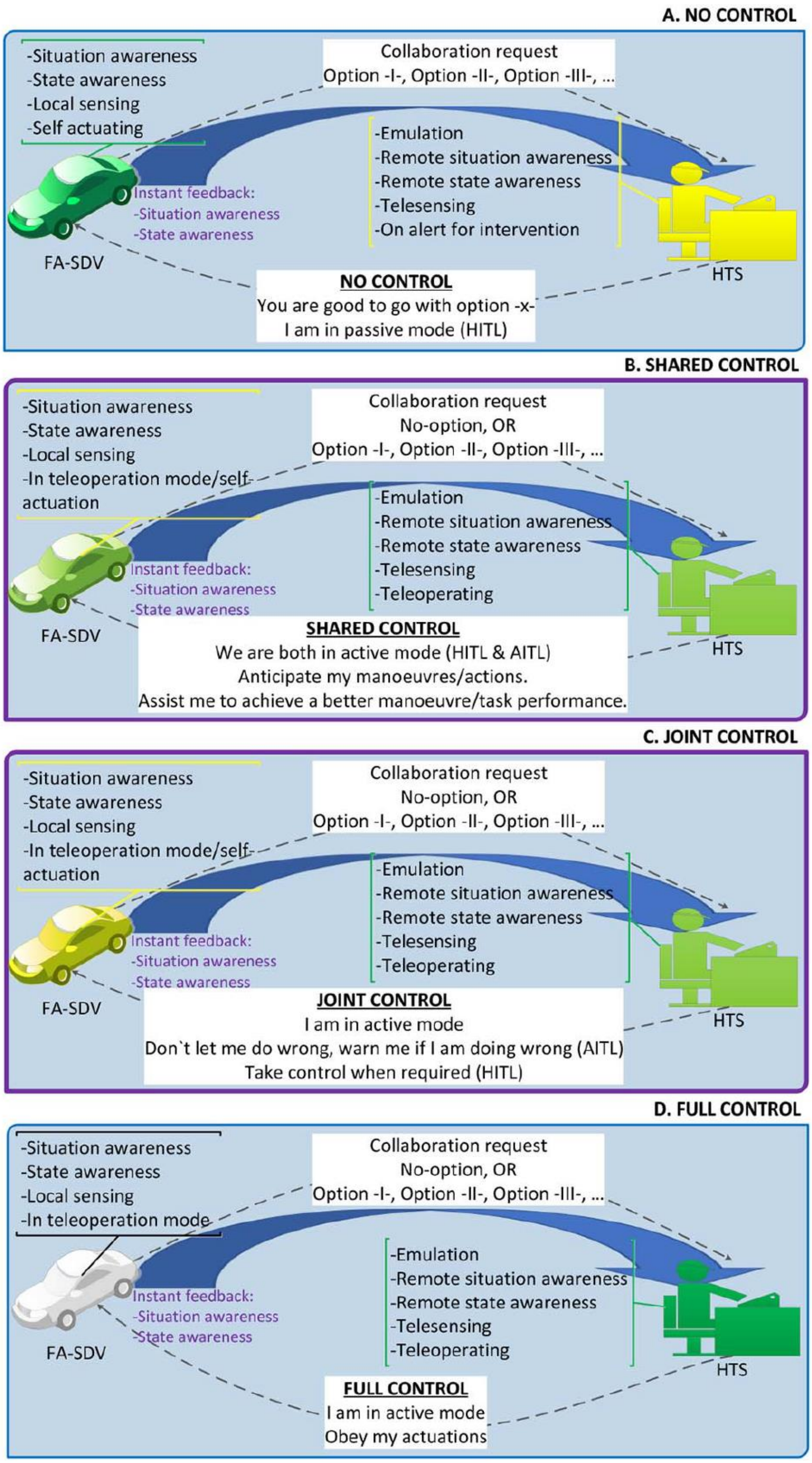

Figure 2: Collaboration modes of HITL haptic teleoperation with a high level of transparency.

Joint-control mode (Fig. 2 C): 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. The HTS may need to take control for some 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 (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. 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.

Full-control mode (Fig. 2 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 other options such as Smart City (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.

3. EVALUATION OF THE INTERVENTION MODES

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

The main distinctive features of the collaboration modes are summarised in Table 1. 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 [13]. 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.

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

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.

4. DISCUSSION

Autonomous Vehicles (AVs), with self-learning and self-decision-making abilities by executing non-trivial sequences of events with decimetre-level accuracy based on a set of rules, control loops and constraints are taking their indispensable places with little or no human in the loop [2] to accomplish various tasks (e.g., [14]). Sensors are the main components of AVs paving the way for autonomous navigation by providing AVs with the ability to perceive the environment through continuous vehicle-environmental interaction [15]. Vehicle sensors, with multiple sensor data fusion, feed the main phases of self-driving, i.e., vehicle learning and decision-making, which are instilled with advanced AI and Federated Learning (FL) [16]. 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— AI agent — is confused about what to do next while performing a task. Until FA-SDVs become completely self-dependent with expedited vehicle self-learning capabilities, HITL 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. HITL teleoperation with FA-SDVs requires real-time ultra-responsive bidirectional interactions and seamless communications — ultra-high reliability, ultra-high availability, and ultra-low latency communication beyond ultra-reliable and low-latency communication (URLLC) regarding the use of SDVs in urban environments considering proper motion synchronisation and accurate rendering of the vehicle-environment. In this way, the mismatches between the real-world vehicle time-varying environment and the cyber-world emulation of this environment can be reduced to an acceptable level.

5. CONCLUSION

Fully driverless vehicles on roads in the future will impact cities significantly and a new sub-domain — "smart management of fully driverless vehicles" — will be incorporated into the ``smart traffic domain'' [17]. 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 [18]. Therefore, remote problem-solving abilities should be incorporated into FA-SDVs during their design and development phases. This report addresses human-vehicle collaboration in delay-sensitive HITL teleoperation with FA-SDVs. To the best of the observed knowledge, this is the first comprehensive report that highlights a research gap in real-time HITL teleoperation with FA-SDVs considering the collaboration modes between two intelligent agents — HTSs and FA-SDVs — in achieving tasks efficiently while the data is being seamlessly transmitted between DTs of real-world self-driving environment and virtual worlds in a highly transparent communication ecosystem through a near-real-time communication and data sharing interface between physical vehicles and virtual vehicles. in this report, an in-depth discussion is provided on building an ideal location-independent collaboration between skilled HTSs and intelligent FA-SDVs. HITL teleportation with critical, cost-effective and timely interventions as elaborated in this report, by enabling omnipresence, can be instrumental in empowering FA-SDVs to cope with many uncertainties instantaneously.

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