Teleoperation Technologies for Enhancing Connected and Autonomous Vehicles

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***Abstract*—Nowadays, fully connected and autonomous vehicles (CAVs) are not completely feasible. Teleoperation promises to be a key and promising solution for bridging the gap between current autonomous driving capabilities and the widespread adoption of CAVs. It allows CAVs to be monitored and (partially) controlled from a distance by remote operators in challenging or unexpected scenarios beyond the vehicle's autonomous driving skills. This paper defines teleoperation before discussing its significance for CAVs. After introducing teleoperation regulations, it highlights technical considerations, improvement techniques, and evaluation criteria for teleoperation performance. Next, it summarizes major research efforts of prominent automotive teleoperation participants and different teleoperation use cases. Finally, this paper concludes with a discussion of research challenges and future research directions.**

I. INTRODUCTION

Background: The proliferation of communication, sensors, and artificial intelligence (AI) has pushed the horizon of connected and autonomous vehicles (CAVs). There has been an acceleration in the research and development (R&D) efforts to bring the idea of CAVs to fruition. For instance, the advent of Tesla's Autopilot, Google's Waymo, General Motor (GM)'s Cruise, and Baidu's Apollo both brought CAVs to the spotlight. The global market of CAVs has maintained an annual growth rate of 12.7% since 2015, reaching \$818.6B in 2019 and is expected to grow up over \$3000B by 2030 [1].

A. Human-in-the-Loop Controlling

Regarding CAVs, the Society of Automotive Engineers (SAEs) defines six levels of autonomous driving (from Level 0 to Level 5) based on the degree to which the vehicle requires human intervention (*i.e.,* human-in-the-loop controlling) [2], as summarized in Table I.

Nowadays, commercial Level 3 CAVs are available (*e.g.,* GM's Super Cruise and vehicles with Tesla Autopilot). They can drive autonomously in desirable situations and have human drivers take control of vehicles when needed [3]. Regarding Level 4 CAVs, leading automotive companies (*e.g.,* Waymo, GM, and Argo AI), test their Level 4 CAVs in predetermined areas and under normal conditions (*e.g.,* daytime and great weather). Although Waymo's Level 4 robotaxi (autonomous taxi) trial in Arizona involved human remote operators, these vehicles still require in-vehicle human drivers.

B. Far From Level-5 Fully Autonomous Driving

Despite the remarkable achievements of CAVs to date, there is still a long way to go before SAEs Level 5 CAV is truly realized due to the frequently encountered technical challenges and unexpected driving conditions [4]. For example, most Level 3 or Level 4 CAVs are now restricted to predesignated routes, or their functionality is specifically optimized for certain areas (such as autonomous parking and highway driving) [3], [5]. However, when testing these vehicles in unfamiliar environments, some of them simply stopped driving due to unresolved environment perception and decision-making problems [6].

In this context, to better exploit the potential of today's CAVs without compromising driving safety, a promising interim solution is teleoperation, which complements autonomous driving systems through the involvement of human intelligence. As a result, it can make CAVs more capable and help them navigate in tricky situations that they cannot handle on their own. We believe that the development of teleoperation technologies will provide a promising direction to evolve toward fully CAVs.

The rest of this paper is organized as follows. Section II defines teleoperation before introducing the significance of teleoperation in Section III. Section IV summarizes teleoperation regulations, and Section V highlights technical considerations and enhancement techniques, along with evaluation criteria of teleoperation performance in Section VI. Then, Section VII outlines major research efforts of prominent automotive teleoperation participants and use cases. Section IX presents a discussion of research challenges and future research directions. Finally, Section X concludes the paper.

II. WHAT IS TELEOPERATION?

Teleoperation is not a new concept. It literally means to operate from a distance and can be traced back to the advent of remotely controllable weapons in the 1870s [7]. Today, there are a variety of machines that can be operated remotely, from remotely-controlled toys to the rapidly growing number of drones, where human perception and operation can be extended to distant places through teleoperation.

A. Definition of Teleoperation in Mobility

As explained in Section I, fully CAVs still face uncertain deployment timeframes, ranging from years to decades. One promising interim solution that several prominent automotive players are exploring is teleoperation, where a remote operator is able to supervise a vehicle with manual intervention via (wireless) communication channels when necessary.

Specifically, a remote operator gathers information about the driving environment (*e.g.,* live views fed by the vehicle's camera or LiDAR) from a remote office or outside the vehicle. The remote operator then provides timely advice or commands related to completing tasks that vehicles are not good at, but humans are (*e.g.,* interpreting sensor data or interacting

TABLE I: The six levels of autonomous driving defined by SAEs.

	Human Drives the Vehicle			**Automated System (When Activated) Drives the Vehicle**		
	Level 0 (No Automation)	**Level 1 (Driver Assistance)**	**Level 2 (Partial Automation)**	**Level 3 (Conditional Automation)**	**Level 4 (High Automation)**	**Level 5 (Full Automation)**
Driver	Performs all driving tasks	Manually control vehicle	Remain engaged with driving tasks and stay fully alert at all times	Must be always ready to take over driving at all times	Can be a passenger who can take control of the vehicle when autonomous driving functions are unable to continue	No driver required
Vehicle	Responds to driver's operation	Provide basic driving assist features: *e.g.,* emergency braking	Perform steering, acceleration, and braking in limited situations	Take full control over steering, acceleration, and braking under certain conditions	Perform driving tasks under nearly all conditions	Perform all driving tasks under all scenarios

directly with other humans next to the vehicle). The above processes may be assisted by varying levels of vehicles' own automation and intelligence.

Fig. 1 visualizes the core concepts of teleoperation for a CAV. A human remote operator assists the vehicle's decision-making process, helping it to act efficiently and correctly in complex and unexpected situations. It mitigates the risk of a fully remote operation via wireless networks, as the vehicle maneuvers in tandem with its own automation capabilities and AI, instead of always handing over full control to a remote operator.

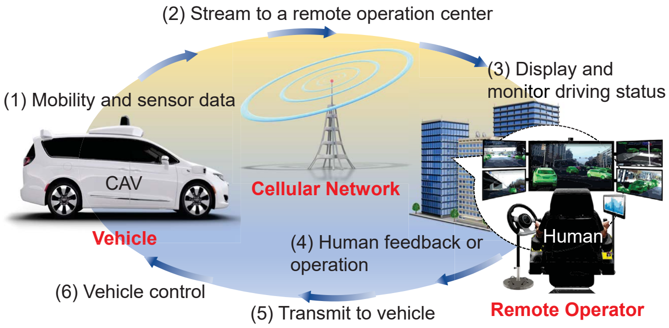

Fig. 1: Schematic diagram of teleoperation. Vehicle's data stream to a remote operation center through communication channels (*e.g.,* satellite connections and cellular networks). Remote operators provide feedback or commands to vehicles via a designed user interface.

B. Three Levels of Teleoperation

Nowadays, it is an agreement that the teleoperation of CAVs can be broadly divided into three levels:

1. **Remote monitoring of vehicles:** This level of teleoperation refers to the remote real-time monitoring of how CAVs are driving. CAVs are equipped with a combination of advanced sensors (*e.g.,* stereo cameras, LiDARs, and short- and long-range radars) that generate large amounts of data per second. The generated data is sent to a remote center via a wireless network in a secure and low-bandwidth manner (*i.e.,* typically the data is encoded and compressed). The remote center decodes the received data for vehicle monitoring and saves historical data. Both real-time data and historical data are imported into a database. In the meanwhile, an edge server provides web pages for remote operators to monitor the driving status of vehicles and analyze historical data for further model improvement. In this way, remote monitoring is able to provide a wealth of useful information to improve the quality and capability of autonomous driving software.
2. **Remote assistance to vehicles:** This level of teleoperation is an *indirect control* method that assists CAVs in the decision-making process to proceed and complete specific tasks. This typically involves the autonomous system providing a menu of choices for the remote operator to select, or the remote operator issuing *high-level* commands by incorporating human intelligence (*e.g.,* answering specific questions, choosing a departure path, or mapping a new route forward) when CAVs encounter unexpected and low-confidence driving scenarios (*e.g.,* construction zones, encountering obstacles, crowded parking spaces, difficult off-road terrain, deadlocked at an intersection because the right-of-way owner is not moving). CAVs decide for themselves how to proceed practically.
3. **Remote control of vehicles:** This level of teleoperation typically refers to real-time and *direct control* (*e.g.,* remote driving) over a considerable period of time. Remote operators are able to control vehicles' steering, brakes, and gas pedals by delivering *low-level* commands with explicit instructions on how to facilitate the operations (*e.g.,* turn 20 degrees right and accelerate speed by 10%). In this case, the teleoperated CAVs are not fully autonomous, as the human is still in control of the vehicle. Remote control is mostly considered as a complementary tool to accomplish tasks in the presence of obstacles, challenging road conditions, sensor failures, and difficult or dangerous driving situations (*e.g.,* off-road terrain) by incorporating human input in real time.

III. WHY IS TELEOPERATION NECESSARY?

Teleoperation helps CAVs navigate difficult situations to obtain early CAV deployments with satisfied safety assurance for promising mobility use cases. Detailed motivations for teleoperation are discussed below.

A. Challenges of Fully Autonomous Driving

*1) **Environment perception and recognition failures under complex scenarios:*** In a CAV, a deep learning-powered system and AI algorithms both play a vital role in helping the vehicle understand and properly respond to the driving environment. However, with the widespread adoption of CAVs, news of vehicle collisions also arise, as shown in Table II. The National Highway Traffic Safety Administration's report revealed that there were nearly 400 crashes involving partially or fully CAVs over a 10-month period [8].

All these statistics show that a large number of CAV accidents are caused by environment perception and recognition failures. This is mainly because the inference performance of CAVs relies heavily on machine learning models trained on specific datasets, and when actually deployed to challenging scenarios with severe occlusions or extreme lighting conditions (*e.g.,* night and rain), CAV systems will suffer from inevitable performance degradation. Hence, in the practical deployment and application of CAVs, teleoperation is urgently needed to bring human intelligence to solve the challenges of environment perception and recognition under complex conditions.

TABLE II: Verified fatal accidents of CAVs.

Company	Failure Reason	Place
Tesla	Fail to recognize people beside a truck	Agder, Norway
Tesla	Fail to recognize a white semi-trailer	FL, USA
Tesla	Fail to detect lane change and alert the driver	Tokyo, Japan
Tesla	Fail to recognize the highway driver	CA, USA
Uber	Fail to recognize pedestrians at night	AZ, USA
Tesla	Mistook a truck for the open sky	FL, USA
Tesla	Fail to recognize a truck under a thick haze	Hebei, China

2) ***Long downtime under unacquainted environments that CAVs cannot handle****:* Regarding unknown environment interpretation in CAV deployment (*e.g.,* exotic cities, construction zones, boxed-in vehicles, and chaotic parking lots), most methods are limited to a shallow level of information, as simple as color changes and position shifting. Such a limitation also hinders uncertain data utilization.

A typical industrial solution is brute-force, collecting as much large-scale training data as possible in an attempt to cover as many uncertain environments as possible. Nevertheless, no matter how vigorous the data collection and annotation, CAVs will still encounter unknown situations. Even an idealized CAV capable of handling 99% of driving situations on its own would still be stuck for 8 minutes during a 12-hour driving day. Even in this idealized scenario, this downtime is completely unacceptable from both a safety and customer experience perspective [9]. Therefore, in this case, teleoperation is needed help to solve unknown driving situations (so-called edge cases) for CAVs. The strategy is to turn edge-cases into known driving events that the CAV can handle when encountered in the future.

B. Unexpected malfunction of sensors & invalid sensor data

Furthermore, CAV sensors have been chronically subjected to extreme deterioration due to various mechanical and weather conditions, inadequate maintenance, and deficiencies in inspection and evaluation. Hence, it is normal to meet the *malfunction of sensors* due to the electrochemical reactions and aging process. Besides, even the sensor themselves are working correctly, the *generated data may still not reflect the actual scenario* and report the wrong information or useless information. For instance, when the vehicle is driving, the camera may be suddenly blocked by unknown objects (*e.g.,* leaves, mud, or a dragonfly), and the radar may deviate from its original fixed position due to wind force. In such cases, CAVs may not be able to navigate themselves by analyzing invalid sensor data, which calls for teleoperation, an effective and necessary solution to unblock and ensure safe vehicle trip progression.

IV. TELEOPERATION LEGISLATION AND STANDARDS

To date, no less than 41 states in U.S. have enacted regulations for CAVs. As discussed in Section III, teleoperation is necessary for the widespread adoption of CAVs. Thus, well-developed regulations for teleoperation will help pave the way.

A. Legislation Status

1) ***U.S. state regulations****:* In the U.S., California incorporated teleoperation into its regulation of CAVs in 2018. Various other states, including Arizona, Michigan, Florida, Ohio, and Texas, have mandated teleoperation as part of their CAV regulations to aid in the testing of CAVs [10], [11]. Other states, such as Nebraska, Nevada, Georgia, North Carolina, and Tennessee have enacted regulations that allow teleoperation but do not explicitly mandate it [11].

2) ***Regulations in other countries****:* In addition to the United States, several other countries have added teleoperation to their CAV regulations, such as Canada, the U.K., Sweden, Finland, and the Netherlands. China has also included teleoperation as part of its CAV regulations in Shanghai [10].

3) ***An example: teleoperation regulations in Germany****:* Germany is a pioneer in teleoperation [10]. In 2021, it approved the new regulations for Level 4 CAVs that do not require active involvement of the human driver in the vehicle. This allows CAVs to be commercially deployed on German roads. As part of this groundbreaking initiative, Germany has included teleoperation in the law, stating that humans must be able to intervene from a distance. To avoid confusion and abuse, the new law clearly stipulates that:

(i) Manual remote driving is not allowed, only indirect control (teleoperation is intentionally referred to as "technical supervision" to clarify role differentiation).

(ii) It is up to the automated driving system (ADS) to determine when a teleoperation session needs to be initiated. Teleoperation occurs only under minimal risk conditions and performs minimal risk operations, such as bringing CAVs to a safe stopping point while turning on the hazard lights. Only in exceptional cases (*e.g.,* in the case of a cyber security attack) can a teleoperation session be initiated directly from the remote operation center.

(iii) The ADS is always in control of and responsible for the driving. Even if ADS receives a command from a remote operator, it decides when and how to execute the command safely.

(iv) The remote operator is not required to monitor CAVs remotely on a one-to-one basis, but on an as-needed basis.

(v) It is mandatory to ensure continuous data transmission over cellular networks.

This example demonstrates how Germany is leading the way in the regulation of teleoperation. While teleoperation legislation has been lagging behind CAV technology, it is starting to catch up.

B. Teleoperation Standards

Currently, U.S. government entities, such as NIST (National Institute of Standards and Technology), have acknowledged the need for teleoperation of CAVs. However, there is still no clear teleoperation standards. An official definition of teleoperation may be provided in the next version of SAE J3016, which is likely to be a starting point for teleoperation standards [11]. The NIST Vehicle Teleoperation Forum [12] and the Teleoperation Consortium [13], are two major non-profit organizations expected to drive the development and evolution of teleoperation standards.

V. TECHNICAL CONSIDERATIONS AND IMPROVEMENT TECHNIQUES

A. Technical Considerations in Teleoperation

Connectivity, system architecture, and the remote display of critical driving environments are vital factors for safe and reliable teleoperation [14].

(i) **Ultra-reliable, high-capacity, and low-latency connectivity** is key to supporting the entire CAV teleoperation session. The timely delivery of high-resolution video, audio, and data from multiple vehicle sensors to remote operators relies on the *ultra-reliable, high-capacity, and low-latency* connection between the CAV and the remote operation center. This is especially critical when it comes to video transmission. For example, high-resolution video transmission normally requires at least 4-10 megabits per second [14]. However, the unstable nature of cellular networks makes it a challenge to consistently achieve this level of performance in a moving vehicle.

(ii) **Advanced system architecture** is another important technical factor in integrating the vehicle software and the teleoperated hardware into a single unit. Depending on the level of teleopration, the corresponding control interfaces must be well designed and implemented (*e.g.,* control interfaces for handling vehicle steering, accelerator, and braking). In addition, an advanced system architecture should be able to coordinate the effective interaction between hardware and software to ensure higher utilization of resources and lower response time of the system, while keeping the addition of new hardware to a minimum for lower SWAP (space, weight, and power).

(iii) **Remote display of critical driving environments** is equally important and challenging. Safe and effective teleoperation requires extremely low latency levels to ensure that the remote operator has real-time situational awareness of the distant driving situation. DriveU.auto points out that only relevant and critical information should be presented [14], as remote operators can be inundated with unnecessary data that can sometimes cause more harm than good.

B. Improvement Techniques for Teleoperation

The improvement methods for teleoperation involve several research domains such as control, communication, sensor, AI, edge computing, security, and so on. In this section, we broadly divide teleoperation improvement methods into four main categories, including operator perception enhancement, interface improvement, control system improvement, and latency compensation. Each of these approaches is described in detail below.

1) Operator perception improvement: Accurate perception of driving space, environment, and motion helps remote operators make the right decisions quickly. According to [7], the research community has conducted experiments in the following areas:

- **Viewpoint shifting**: shifting the egocentric view of the captured environment (first-person perspective) to an exocentric view (third-person perspective) to gain a broader perspective.
- **Automatic view adjustment**: changing the viewpoint from a fixed viewpoint to a flexible one so that the desired viewing direction can be automatically predicted and adjusted.
- **Stereoscopic vision**: building a 3D scene based on visual inputs from two vision sensors, also called stereo vision, can provide remote operators with better environmental perception through depth estimation.
- **Map merging**: combining visual information collected by one or more CAVs to achieve a more comprehensive view of the driving environment.
- **Vibro-tactile feedback**: delivering non-visual human sensory information to the remote operator, such as audio, force, and haptics, to provide additional information about the remote environment (*e.g.,* incorporating vibrotactile feedback into the teleoperation process).

2) Immersive interface for virtual driving environment: A virtual driving environment refers to the reconstruction or simulated experience of the real driving world. The user interfaces currently provided to remote operators allow the use of special devices such as joysticks and steering wheels. However, these interfaces lack additional feedback, such as motion and vibration, to help the remote operator precept the environment.

One enabling technology is augmented reality (AR), a form of interactive experience that immerses the remote operator in the vehicle environment with a high degree of perceptibility. Designing an immersive interface (one that triggers a 3D virtual reconstruction) and wearing commercially available AR glasses and headsets (if necessary) can improve communication between CAVs and remote operators through spatial dialogue and intuitive visual signals.

3) Control system improvement: Improving CAV control systems to make teleoperation easier has been a long-standing research topic [7]. We classify such approaches into three broad categories as follows.

- **Control policy improvement**: intelligent control strategies can improve the controllability of teleoperated vehicles. For example, compensation and gain adaptation algorithms can be applied to set speed references by combining the remote operator's speed commands, sensor feedback, and the vehicle's current state with time delays.
- **Increasing local autonomy**: Since full CAV remains a long-term future research topic, improving autonomous capabilities for decision making (*e.g.,* automatic collision avoidance, real-time diagnostics, and trajectory planning), could be an effective way to improve teleoperation performance.
- **Implementing automatic tracking**: It can be very difficult for a single remote operator to control multiple vehicles at the same time. Therefore, by ensuring that the control of the lead vehicle automatically tracks subsequent vehicles, the workload of teleoperation of a CAV fleet can be significantly reduced.

4) Latency compensation: Communication delays between CAVs and remote operators are unavoidable. In challenging environments, long and time-varying delays can even make effective teleoperation impossible [7]. The following discusses two potential methods for latency compensation.

- **Predictive display**: the communication and control loop delays have led to the development of predictive displays, which show the current and future locations of all observed vehicles. It also allows remote operators to view the response of the CAV system before it actually occurs, thus avoiding possible collisions and mitigating the high space-based delays.
- **Parallel virtual vehicle control**: create some form of parallel virtual vehicle environment that displays the immediate responses of CAVs to remote operators on a virtual interface, *i.e.,* the state of the calibrated virtual vehicle is represented on the user interface, before sending real control signals through the communication loop. Thus, the remote operator can generate action commands prior to receiving actual visual feedback from the environment.

VI. EVALUATION CRITERIA OF TELEOPERATION PERFORMANCE

Teleoperation is a complex cross-disciplinary research domain. Due to differences in vehicle and interface types, control technologies, driving conditions, and various types of mobile services, a predefined set of evaluation metrics may not provide valid judgments for all scenarios, and it is challenging to develop a unified evaluation technique for CAV teleoperation. In this section, we present a set of potential evaluation techniques that can be used.

According to [7], remote operators can test the performance of the teleoperation by having CAVs perform simple tasks, such as passing the vehicle over a predetermined track, identifying objects, or simply operating the vehicle to stop near an obstacle. Quantitative evaluation criteria may include but are not limited to, the completion time of multiple tasks, the speed at which the vehicle moves, the number of collisions with obstacles, the actual location of the vehicle compared to the target location, the distance the vehicle travels in a given time, the number of commands executed, the number of missed tasks, and the actual trajectory compared to the target trajectory. A future research direction for teleoperation may be to develop a more general tool to evaluate the overall performance of teleoperation.

VII. PROMINENT AUTOMOTIVE TELEOPERATION PLAYERS

In this section, we dive into the research efforts of major automotive teleoperation players (as shown in Table III).

A. Automotive Technology Company and Startup

Although Tesla is recognized as an early leader in CAVs and is well known for its Autopilot system, it does not appear to publicly claim to use teleoperation [15].

Waymo is a prominent autonomous driving company that operates a commercial autonomous driving taxi service. It has a group of remote operators at its facilities in suburban Phoenix to monitor and assist its ride services [16]. When CAVs encounter low-confidence scenarios where CAVs get stuck, they can answer specific questions about the ambiguous situation by pressing relevant buttons.

Cruise, an autonomous driving subsidiary of GM, aims to commercialize the Cruise fleet through a ride-sharing platform [17]. Passengers are able to communicate with remote operators with the press of a button. Besides, Cruise acquired a CAV startup Voyage [18], which is known for its product named Telessist Pod, a proprietary workstation customized for remote operators [9].

Jaguar Land Rover, a subsidiary of Tata Motors Limited, is a British multinational automobile manufacturer which produces luxury vehicles and sport utility vehicles. It demonstrates how a remote-controlled Land Rover Sport research vehicle can be controlled by a driver from outside the vehicle via a smartphone, in order to traverse an obstacle or leave a parking space [19].

Toyota is one of the largest multinational automotive companies in the world. It develops a teleoperation-enabled control system for both autonomous and semi-autonomous vehicles. Remote operators can manually operate vehicles remotely or issue commands. The captured data sent to the remote operator can be optimized to save bandwidth [20].

Uber is an American provider of mobility-as-a-service. Uber considers teleoperation as a necessary interim step to autonomy, and it is developing teleoperation technologies with industry-standard protocols to keep human-in-the-loop. [21].

Motional is an American autonomous vehicle startup as a joint venture between automaker Hyundai Motor and auto supplier

Aptiv. Motional has collaborated with Ottopia, the global leader in teleoperation, to conduct remote vehicle assistance when operating its Level 4 robotaxi fleets [22].

Aptiv is an Irish-American automotive technology supplier. It is developing its own teleoperation solution which could potentially be done from its Las Vegas operations center [23]. Besides, Aptiv joined the Teleoperation Consortium (TC) [23] and also focused on the teleoperation of unmanned ground vehicles (UGVs) [24].

Drive.AI, a subsidiary of Apple Inc., is an American technology company that uses AI to make autonomous driving systems. It uses teleoperation technologies to guide CAVs to continue to drive in exotic situations or during a stalemate [25].

Aurora is an Amazon-backed autonomous driving technology startup. It believes building a teleoperation system can help ensure public acceptance of its Aurora Driver [15], a computer system for CAVs. Hence, it develops remote control systems called "teleassist" that allow its testing fleets in the Bay Area and Pittsburgh to handle a range of road conditions.

Zoox is an autonomous vehicle startup acquired by Amazon, which is working on CAVs for Mobility-as-a-Service. Zoox has developed TeleGuidance, a key component of the autonomous driving stack, to support teleoperation [26].

B. Teleoperation Providers

Designated Driver is one of the first teleoperation providers. It offers teleoperation-as-a-service for fleets, including trained and certified remote operators and hardware and software kits for the teleoperation [11]. Its products are available through AutonomouStuff, which offers a wide range of CAV products.

Ottopia is a leading automotive-grade teleoperation provider [28]. Ottopia's products include an in-vehicle teleoperation module and a teleoperation center console [11]. To date, Ottopia has partnered with BMW, Denso, Bestmile, EasyMile, Innoviz, Deutsche, Telekom, Gaussin, Via, and May Mobility.

Phantom Auto is a pioneer in the field of teleoperation, offering vehicle-independent teleoperation software solutions with low-latency communications and APIs for remote assistance and remote driving [29]. It is currently powering a wide range of use cases for last-mile delivery, material handling, and yard operations for companies such as Uber, ITS ConGlobal, and Postmates.

Scotty Labs is a Google-backed teleoperation company dedicated to performing teleoperation for CAVs. It teamed up with Voyage, a company aiming to build fully autonomous driving taxi platforms, to support autonomous driving in retirement communities [30].

RoboAuto is a teleoperation startup focused on developing and integrating comprehensive teleoperation services for a variety of industrial vehicles, such as forklifts, excavators, and harvesters, covering demolition, mining, logistics, and mowing equipment [31].

DriveU.auto is a developer of a superior software-based connectivity platform, named DriveU, for autonomous vehicle teleoperation [14]. DriveU's SDK and open APIs enable fast and straightforward integration, and it can be deployed on vehicles' main computing units such as NVIDIA Jetson platforms. DriveU is already deployed and in use on public roads and sidewalks, supporting large-scale autonomous vehicle deployments.

VIII. TELEOPERATION USE CASES

Teleoperation is critical to autonomy across industries, which can be integrated into robotaxis, shuttles, trucks, mining vehicles, flying vehicles, *etc.* Currently, in addition to mainstream CAVs (*e.g.,* Waymo, Cruise, and Zoox robotaxi), sidewalk vehicles (*e.g.,* Kiwibot and Postmates) and industrial vehicles such as forklifts and trucks (port and loading/unloading operations), combines and harvesters (agriculture), and excavators (mining) are also common teleoperation use cases.

(1) **CAV fallback mechanism under challenging and unexpected scenarios**: One of the major obstacles delaying the arrival of fully CAVs is that a myriad of decision-making algorithms need to be trained to respond to countless driving scenarios including edge cases. However, covering all possible real-world scenarios is practically impossible. Therefore, teleoperation is needed to guide CAVs when they encounter new scenarios or unsolvable situations (*e.g.,* complex off-road terrain and crowded parking space), so that the CAVs can safely complete their missions.

(2) **Safety mechanism during CAV trials**: Most CAV tests, whether required by regulations or self-required, are conducted with a safety driver (either remotely or physically). The remote operator is needed to intervene immediately in the event of a dangerous situation to ensure safe driving.

(3) **Food and package delivery**: Teleoperation is already widely used for the last-mile delivery robots and autonomous trucks that handle deliveries from pickup to handover.

(4) **Shared electric scooters**: Teleoperation is also used to move electric scooters to charging stations or to return scooters after a rental usage, which is able to increase operational efficiency.

(5) **Vehicle ride-sharing**: Passengers can use their mobile app to request a ride and control their ride experience with customized radio and climate settings. In addition, passengers can communicate with remote operators at the push of a button to make special requests and report warnings.

(6) **Building demolition**: Normally, building demolition is a dangerous line of work. Teleoperation provides a new method by transferring human workers to a safe distance, which can better guarantee work safety and make better utilization of drivers.

(7) **Logistics in large or dangerous area**: Leverage teleoperated vehicles to transport materials in large (and dangerous)

TABLE III: A summary of major automotive teleoperation players.

Company	General Infomation	Research Efforts in Teleoperation	Application Scenarios of Teleoperation
Waymo [16]	• Automotive technology company • Founded date: 2009 • Headquater: Mountain View, California, United States	• Remote operator watch real-time video from eight cameras of each vehicle • Do not manipulate vehicles, but answer specific questions under an ambiguous situation based on human understanding	Answer specific questions when the vehicle encounters unacquainted environments (*e.g.,* encountering a flock of pigeons, a wrong turn, or a construction zone) and gets stuck
Cruise [17] [9], [18]	• Automotive technology company • Founded date: 2013 • Headquater: San Francisco, California, United States	• Commercialize Cruise fleets through a ride sharing platform and allows passengers to communicate with remote operators with the press of a button • Acquired Voyage, an autonomous vehicle startup known for its product called Telelessist Pod, a customized workstation for remote operators	• Ride-share • Ride experience enhancement
Jaguar Land Rover [19]	• Automotive technology company • Founded date: 2008 • Headquater: Whitley, Coventry, United Kingdom	• Drivers can serve as remote operators to control vehicle steering, brake, and accelerator via a smartphone app to maneuver their vehicle safely out of challenging situations • Only operate teleoperation if the user is within 10 meters of the vehicle and if the smart key can be detected	• Traverse an obstacle under complex situations such as difficult off-road terrain • Exit a crowded parking space
Toyota [20]	• Automotive technology company • Founded date: 1937 • Headquater: Toyota, Aichi, Japan	• Send a subset of data captured by vehicle's various cameras, radar, and LiDAR sensors to remote operators • Remote operators could either control the vehicle directly or issue commands for CAVs to execute	Guide or control vehicle when it encounters an unacquainted driving environment (*e.g.,* road construction or an obstruction) for autonomous operation
Uber [21]	• Mobility-as-a-service provider • Founded date: 2009 • Headquater: San Francisco, California, United States	• Develop its teleoperation technology with industry-standard protocols to keep human-in-the-loop rather than control • Remote operators are trained in the remote assistance and autonomous system, but they are not specifically trained in steering, braking, or other driving maneuvers.	Teleoperation is typically used to unblock vehicle trip progression
Motional [22]	• Automotive technology startup • Founded date: 2020 • Headquater: Boston, Massachusetts, United States	Leverage teleoperation technology to conduct remote assistance when operating its SAEs Level 4 CAVs	Provide remote vehicle assistance to the robotaxis for fully autonomous ride-hail services
Aptiv [23] [23] [24]	• Automotive technology supplier • Founded date: 1994 • Headquater: Troy, Michigan, United States	• Develop its own teleoperation solution (possibly from the Las Vegas operations center) • Joined the Teleoperation Consortium (TC) • Support teleoperation for unmanned ground vehicles	Teleoperation of a passenger-sized unmanned ground vehicles in path-following scenarios at varying speed
Drive.AI [25]	• Automotive technology company • Founded date: 2015 • Headquater: Mountain View, California, United States	• Remote operators answer specific questions under a special driving scenario based on human understanding • The decisions that a remote operator makes will also be fed back to vehicle's learning software to improve its decision-making capabilities	Guide vehicle to drive during a stalemate or under exotic situations (*e.g.,* right-of-way has shifted to pedestrians, but they are just standing there and waiting to see what the vehicle does)
Aurora [15]	• Automotive technology startup • Founded date: 2017 • Headquater: Pittsburgh, Pennsylvania, United States	The developed system named "teleassist" will alert remote operators when the need arises, allowing its testing fleets in the Bay Area and Pittsburgh to handle a range of road conditions.	Provide advice and guidance under abnormal scenarios to adapt to a variety of vehicle types and use cases (*e.g.,* long-haul trucking, local goods delivery, and people movement)
Zoox [26]	• Automotive technology startup • Founded date: 2014 • Headquater: Foster City, California, United States	Develop TeleGuidance, a key component of the autonomous driving stack, to incorporate human contextual guidance into vehicle's motion planning algorithms	Dealing with challenging scenarios and correct vehicle's perception results by fusing human input in real time to complete the mission (*e.g.,* object recategorization and path planning)
Designated Driver [11] [27]	• Teleoperation company • Founded date: 2018 • Headquater: Portland, Oregon, United States	• Offer teleoperation-as-a-service for fleets, including trained and certified remote operators and hardware and software kits • Offer both remote driving and remote assistance • Provide teleoperation for fixed route shuttles (collaborated with Texas A&M university)	Enabling vehicle remote control in the event of obstructions, challenging road conditions, sensor malfunction or where operation is difficult or hazardous
Ottopia [28] [11]	• Teleoperation company • Founded date: 2018 • Headquater: Tel Aviv, Israel	• Offer both remote assistance and remote driving aiming to address the core challenges in teleoperation (*e.g.,* network connectivity, safety, and cybersecurity) • Ottopia's product include an in-vehicle teleoperation module and a teleoperation center console • Ottopia has partnered with BMW, Denso, Bestmile, EasyMile, Innoviz, Deutsche, Telekom, Gaussin, Via, and May Mobility.	• Remote operators assist in decision-making processes in complex scenarios • Enable the manual control of vehicles by a remote human remote operator
Phantom Auto [29]	• Teleoperation company • Founded date: 2017 • Headquater: Mountain View, California, United States	• Complement vehicle autonomy by remotely monitoring many vehicles simultaneously and "zooming in" on target vehicles for more precise remote control when needed • Enable humans sitting up to thousands of miles away to fully remotely operate material handling vehicles (*e.g.,* forklifts, tuggers, and yard trucks in intermodal shipping areas) • Teleperators can draw a path for a Postmate (an on-demand small-size delivery vehicle) to follow	Powering a wide range of use cases for material handling, yard operations, and last-mile delivery for companies such as Uber, Postmates, and ITS ConGlobal.
Scotty Labs [30]	• Teleoperation startup • Founded date: 2017 • Headquater: Menlo Park, California, United States	• Leveraging teleoperation to solve challenges under complex edge cases while allowing the company to focus on improving their autonomous driving technology • Teamed up with Voyage, a company aiming to build a fully autonomous driving taxi platform	Supporting a fully autonomous driving taxi platform in retirement communities
RoboAuto [31]	• Teleoperation startup • Founded date: 2017 • Headquater: MBrno-Královo Pole, Czechia	Developing comprehensive teleoperation services for various industrial vehicles, such as forklifts, excavators, and harvesters, covering demolition, mining, logistics, and mowing equipment	• Logistics in factories • Building demolition • Mowing around highway or difficult terrain
DriveU.auto [14]	• Teleoperation platform provider • Founded date: 2019 • Headquater: Kfar Saba, HaMerkaz, Israel	• Develop DriveU, a connectivity platform for teleoperation, is already deployed and in use on public roads • The product's SDK and open APIs enable fast and straightforward integration. • The DriveU platform can be deployed on NVIDIA Jetson platforms (*e.g.,* Jetson Xavier NX, Jetson AGX Xavier, and Jetson Nano GPU-accelerated systems-on-module)	Transporting goods with autonomous trucks, making roadside deliveries from the comfort of office, operating heavy machines remotely, and monitoring autonomous shuttles

areas such as chemical facilities, factories, or refineries. Since all operations are performed from a remote operation center, and one operator can monitor or control multiple vehicles at the same time, teleoperation can protect operators' safety and increase work efficiency.

(8) **Mowing around highways or difficult terrain**: Mowing in difficult terrain, around highways, on steep hills, or in hot temperatures can be a major obstacle for the operator. Teleoperation makes this type of work easier and safer.

(9) **Minning**: The excavator in the digging area is either working or waiting [31]. Teleoperation allows the remote operator to skip the waiting step, as remote operators can disconnect the vehicle currently in use and quickly connect to another vehicle to continue the excavation work.

IX. RESEARCH CHALLENGES AND FUTURE DIRECTIONS

Conducting efficient and effective teleoperation for a moving CAV on a public road is a very complex task, as it aims to make sure the vehicle can recognize and interact with all possible objects on all types of roads in all possible traffic, weather, and visibility conditions. In this section, we discuss principal challenges known to be especially important for teleoperation.

A. Research Challenges in Teleoperation

1) Limited Bandwidth: Teleoperation requires real-time transmission and display of high-quality video, sensor data, and various types of commands. Low bandwidth can cause delays in video and information transmission, which often leads to poor spatial awareness and can miss cues that are critical to environmental awareness. However, distance, electronic interference, or obstructions can both create challenges in maintaining adequate signal strength [3]. Therefore, providing a consistent bandwidth for teleoperation still remains an open problem.

2) Excessive and Variable Latency: The total latency in teleoperation consists of latency of the control commands from the remote operator to the CAV and latency of the feedback from the CAV to the remote operator [3].

(i) **Excessive latency**: A few previous studies have indicated that the total latency below about 170 ms has a slight impact on teleoperation performance [32]. Studies have also shown that when the total latency exceeds 300 ms, remote operators tend to wait for feedback on the previous command before issuing the next command, instead of sending successive commands, which becomes more pronounced as the latency increases [32]. Some works have also shown that when the total delay exceeds 700 ms, vehicle teleoperation performance decreases significantly to the point of being largely infeasible [33].

(ii) **Variable latency**: In addition, variable latency causes more severe degradation of remote operation performance than constant latency [33]. The larger the standard deviation of the delay, the more it degrades the remote operator's control of the vehicle. Therefore, an important problem is how to maintain adequate vehicle teleoperation performance and safety when the latency is highly variable.

3) Safety Under Poor Network Conditions: Furthermore, previous work highlighted that it is vital to consider the driving scenario when remote operators lose control of CAVs due to poor network conditions [3]. In this case, both remote operators and CAVs must be able to do the following accurately in a timely manner.

(i) **Predicting disconnections**: Remote operators and CAVs should be able to accurately predict the disconnection time point and disconnection period.

(ii) **Appropriate precautions**: Next, remote operators or vehicles should quickly take necessary proactive operations in advance (*e.g.,* reducing driving speed, pulling over or stopping the vehicle, avoiding complex maneuvers).

(iii) **Self-rescue in case of unexpected disconnections**: If the remote operator suddenly loses control of the CAV, the vehicle should perform a self-rescue maneuver to put itself in safe mode until the remote operator regains control.

4) Other Challenges of Teleoperation: Below summarizes the other four potential challenges of teleoperation [7].

(i) **Exploring optimal parameters for user interface**: One of the challenges in developing a visual assistive user interface for remote operator, is figuring out the optimal parameters for a scene (*e.g.,* the field of view, the number of video feeds, and the acceptable resolution)

(ii) **Trade-off of diverse factors**: Achieveing a good trade-off between vehicle types, mobility tasks, teleoperation methods, vehicle speed, video frame rates, pixels per frame, and bits per frame (*i.e.,* levels of brightness or grey-scale) is another challenge for teleoperation.

(iii) **Uncertainty of remote operators**: The high number of high-latency teleoperation tasks is very stressful for remote operators, and they are prone to fatigue and perform over-correction, leading to wrong operations. However, existing systems do not take into account the uncertainty of the remote operator, *i.e.,* lack of real-time monitoring of the remote operator's physical status.

(iv) **Overwhelmed monitoring information**: Multi-sensor remote operating systems often provide overwhelming monitoring information. It is essential to design an interface and system to achieve an easy-to-understand display of the driving environment.

B. Future Directions

Autonomous CAV teleoperation: To date, CAV teleoperation fully relies on human remote operators. Zhang *et al.* [3] believe that the teleoperation system will become increasingly more intelligent, *i.e.,* the AI-powered cloud or edge devices are able to provide advanced assistance to human remote operators (*e.g.,* predicting network conditions and sending warnings that human remote operators may ignore), which will further push the emerging of autonomous teleoperation.

Here, we summarize several other teleoperation topics that industry and academia may be interested in, including but not limited to: safety of teleoperation, latency and bandwidth reduction in teleoperation, operational design of teleoperation, interfance design for vehicles and teleoperation systems, open and customizable teleoperation systems, and multimodal teleoperation system. In addition, another future research could be the development of a generalized tool to evaluate the overall performance of teleoperation. Besides, collaboratively defining the teleoperation standards will also drive the industry forward.

X. CONCLUSION

CAVs and teleoperation are intrinsically integrated, and teleoperation is on its way to playing an important role in diverse CAV use cases. This paper defines teleoperation before discussing the significance of teleoperation for CAVs. After introducing teleoperation regulations, it highlights technical considerations and improvement techniques, along with evaluation criteria for teleoperation performance. Next, it summarizes major research efforts of prominent automotive teleoperation participants and use cases of teleoperation. Finally, this paper concludes with a discussion of research challenges and future research opportunities.

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