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Teleoperation methods and enhancement techniques for mobile robots: A comprehensive survey☆

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ABSTRACT

In a world with rapidly growing levels of automation, robotics is playing an increasingly significant role in every aspect of human endeavour. In particular, many types of mobile robots are increasingly being utilised in places and for tasks that are difficult and dangerous for humans. Although the vision of fully autonomous mobile robotic platforms that can perform complex tasks without direct guidance from a human operator is compelling, the reality is that the current state of robotics technology is still a long way from being able to achieve this capability outside of very narrowly constrained contexts. Technology advancement for improved mobile robotic teleoperation and remote control is vital to enable robotic vehicles to operate with increasing autonomy levels while allowing for effective remote operation when task complexity is too great for the autonomous systems. Being motivated to bridge this gap, we present a review of existing teleoperation methods and enhancement techniques for control of mobile robots. After defining teleoperation, we provide a detailed review that analyses, categorises, and summarises existing mobile robot teleoperation methods. Next, we highlight existing enhancement techniques that have been applied to these teleoperation methods, along with their relative advantages and disadvantages. Finally, several promising future research directions are identified. The paper concludes with a discussion of research challenges and future research possibilities.

1. Introduction

Due to continuing advancements in the fields of robotics, sensor systems, artificial intelligence (AI), and computer vision, mobile robots are becoming increasingly integrated into modern civilisation. From warfare [1,2] to domestic applications [3], from search and rescue [4] to mining [5], from underwater [6] to aerial [7] and space exploration [8], mobile robots like Unmanned Ground Vehicles (UGVs), Autonomous Underwater Vehicles (AUVs), and Unmanned Aerial Vehicles (UAVs), are becoming increasingly capable [9]. Over the next few decades, reliance on mobile robotic platforms is projected to significantly increase [10].

Representations of mobile robot assisted tasks are most often envisaged as fully autonomous. However, despite the considerable progress that has been made in computing, communication, and sensor technologies, building a mobile robot platform that can perform complex operations and execute a task entirely autonomously requires a long research process [11]. Even platforms capable of high levels of autonomy require some level of human monitoring and external direction due to the complexities of the remote environment. This supervision is achieved through some form of teleoperation, whereby control commands are transmitted to a remote robot over a communication channel, and sensor information, e.g. a camera feed, is transmitted back over the same channel.

Although the conceptualisation and development of teleoperation started as early as the 1900s, the first master–slave teleoperation system was developed during the mid-1940s [12], and the widespread use of teleoperated vehicles did not start before the 1970s [13]. High computation capabilities due to technological advancement in microprocessors and development of programming languages specific for supervisory teleoperation [14,15] has geared up both the research and usage of mobile robot teleoperation throughout the 1990s. Teleoperation using packet data through the Internet started from the mid-1990's [16,17]. However, data and communication transmission through the Internet's packet-switched network induces time-varying delay and

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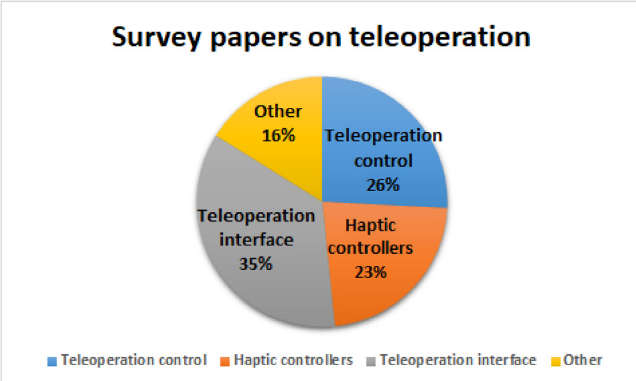

Fig. 1. Proportion of recent survey papers (published in the last two decades) written on each of the identified teleoperation focus areas.

packet-loss issues. Teleoperation of mobile robots over the Internet has been an active research area since [18].

The twenty-first century needs for safer human exploration and mining, environmental observation, better transportation, surveillance, or even space exploration have uplifted the necessity of enhanced mobile robot teleoperation technology. Recent advancements in remote and digital image collection technology [19], machine learning and deep learning techniques [20,21], fast and high performance desktop size computation facilities for real-time applications [22], and human–machine user interfaces [23] have created a perfect time and place combination for mobile robot teleoperation research.

Considering the necessity of teleoperation in robotics, its diversity, and the high volume of research in the domain, a significant number of survey papers and review works have already been published, focusing on different aspects of the problem. Limiting consideration to survey work that has been published within the last two decades, most of these survey works can broadly be categorised into three main focus areas: literature that surveyed and reviewed control theories, implementation techniques, and their applications; literature focusing on the haptic control techniques used in robotic teleoperations; and survey papers reviewing various teleoperation interfaces. The pie-chart in Fig. 1 presents a statistical overview of these focus areas.

From Fig. 1, a large number of survey papers covered the control aspects of robotic teleoperation. Luo et al. [24], Sun et al. [25], and Varkonyi [26] surveyed the control theories used for robotic teleoperation. Lichiardopol et al. [27], Chan et al. [28] and Xia et al. [29] surveyed different control techniques and their applications in teleoperation. Kebria et al. [30] dedicated his review on control techniques used for teleoperation through the Internet only. Haptic controllers are another major focus for the survey works in the last two decades. Salcudean et al. [31] and Cui et al. [32] performed surveys on teleoperation control that specifically focused on haptic interfaces. Li et al. [33], Ryu et al. [34], and Ma and Schilling [35] concentrated their focus on force feedback techniques and their applications in mobile robot and manipulator teleoperation. Muradore and Fiorini [36] reviewed algorithms developed and used for stability and control of haptic teleoperation interfaces.

A number of research groups studied and reviewed teleoperation interfaces. Virtual reality (VR) based interfaces are widely used and surveyed by Tzafestas et al. [37] and Dejing et al. [38]. Nourmohammadi et al. [39] surveyed the techniques and applications of brain–computer interfaces (BCI) in teleoperation. Other older works include review of human–robot interfaces (HRI) by De Barros and Linderman [40] and Batsomboon et al. [41]. Besides, Hokayem and Spong [12] presented a historical timeline based survey on bilateral teleoperation, Goodrich et al. [42] reviewed and discussed humanoid robot teleoperation techniques, Wichmann et al. [43] reviewed sensors and networks used in robotic teleoperations, Liu and Nejat [44] reviewed urban search and rescue teleoperation techniques, and in a very recent work Skorobogatov et al. [45] presented a survey on multi-agent UAV systems. Table 1 presents all the surveys written on teleoperation in the last two decades.

For effective real-time teleoperation of robotic vehicles (UGVs, UAVs and ROVs), particularly when complex tasks need to be performed, enhancement of conventional teleoperation is a necessity. Despite this, to the best of our knowledge, none of the above-mentioned works have focused on enhancement techniques for improved teleoperation of robotic vehicles. Considering this gap, and the growing importance of this area of study, we intend to present an organised survey on teleoperation methods and their enhancement techniques. We have considered the publications from last two decades to inform the readers about the state-of-the-art in the domain. Teleoperation (especially bilateral teleoperation) methods for stationary manipulators and mobile robots are different in terms of the control structure and performance evaluation criteria and hence it is very difficult to introduce both under the same framework. Also the title of the paper, clearly mentions the focus as mobile robots. Therefore, we have included papers that discuss teleoperation and techniques to enhance the teleoperation of only mobile robots as the main focus. This rigorous survey has been conducted based on journal and conference articles, book chapters, review articles, theses, and project reports written in English. We used online databases such as Web of Science, Science Direct, ACM digital library, Google Scholar, IEEE Xplore digital library, Springer, Elsevier, and PubMed.

This paper provides:

1. A categorisation of the teleoperation methods of different mobile robot types based on their modes, operational environment and mobility perspectives.
2. A comprehensive taxonomy (Fig. 7) of the existing state-of-the-art teleoperation enhancement techniques based on critical analysis of the literature.
3. Identification and description of the principle limitations and associated challenges of existing mobile robotic teleoperation enhancement techniques.
4. Possible future research directions to solve the present teleoperation limitations based on an analytical review of existing computer vision and AI-based techniques.

The rest of the paper is organised as follows. Section 2 provides the definition of robotic teleoperation along with the problem overview. Section 3 discusses mobile robots according to their mobility mode. Section 4 categorises and describes different teleoperation methods. Section 5 critically analyses, categorises, and describes all of the state-of-the-art teleoperation enhancement techniques. Section 6 discusses the evaluation criteria of teleoperation performance. Section 7 discusses the relevant research challenges. Some proposed future research directions are offered in Section 8. Finally, Section 9 draws the conclusion.

2. Robotic teleoperation

2.1. What is robotic teleoperation?

The literal meaning of the Greek term ‘tele’ is “far off” or “at a distance” that naturally implies the definition of ‘teleoperation’ as a distant operation. The human capability to sense and manipulate is extended to a distant or remote location by teleoperation [13]. A robot is a machine that is intended to ease

Table 1
Survey papers and their focus areas within teleoperation published over the last two decades.

Author (Year) [Ref.]	Focus of the survey
Teleoperation control	
Luo et al. (2020) [24]	Control theories, HRI and robot learning for telerobots
Kebria et al. (2018) [30]	Control techniques used in teleoperation through the Internet
Varkonyi et al. (2014) [26]	Review of theoretical control solutions for teleoperation
Chan et al. (2014) [28]	Survey on adaptive controllers used in teleoperation
Sun et al. (2014) [25]	Wave variables and their applications in teleoperation to improve performance
Caska and Gayretli (2014) [46]	UAV–UGV collaborative systems formation control
Xia (2013) [29]	Surveys control methods and control system architectures
Passenberg et al. (2010) [47]	Task-adapted controllers for teleoperation systems
Lichiardopol (2007) [27]	Applications and system control techniques
Haptic controllers	
Lie et al. (2018) [33]	Haptic controllers used in teleoperation systems
Muradore and Fiorini (2016) [36]	Algorithms for haptic teleoperation
Pessenberg et al. (2010) [47]	Environment, operator and task adapted controllers used in teleoperation
Ryu et al. (2009) [34]	Haptic control techniques used in teleoperation
Ma and Schilling (2007) [35]	Force feedback rendering and control techniques for force feedback in teleoperation
Cui et al. (2003) [32]	Force reflecting manual controllers used in teleoperation
Salcudean (1998) [31]	Survey on teleoperation haptic controllers
Teleoperation interface	
Szafir and Szafir [48]	Data visualisation techniques for teleoperation interface
Young and Peschel (2020) [49]	HMIs for small platforms with teleoperated manipulators
Makhataeva and Varol (2020) [50]	Augmented reality for robotics
Rea et al. (2020) [51]	Social and psychological interfaces for teleoperation
Murphy and Satoshi (2019) [52]	User interface guidelines for teleoperation
Delmerico et al. (2019) [53]	User interfaces for search and rescue robots
Nourmohammadi et al. (2018) [39]	Application of Brain–Computer Interface (BCI) for UAV teleoperation
Dejing et al. (2017) [38]	Virtual Reality (VR) for teleoperation
De Barros and Linderman (2009) [40]	Human–Robot Interface techniques and applications
Tzafestas (2007) [37]	Applications of VR and Mixed Reality (MR)
Batsomboon et al. (2000) [41]	Discussion of the major techniques of telesensation during teleoperation
Other	
Skorobogatov et al. (2020) [45]	Multiple UAV systems
Opiyo et al. (2020) [54]	Architecture and situation awareness of UGVs
Wichmann et al. (2014) [43]	Wireless sensor networks, and requirements to implement them in teleoperation
Liu and Nejat (2013) [44]	Application of both autonomous and telerobots in urban search and rescue tasks
Goodrich et al. (2013) [42]	Potential techniques and challenges for humanoid robot teleoperation
Hokayem and Spong (2006) [12]	History of bilateral teleoperation

or replace human presence and effort by automatic operation and may or may not resemble human beings both in performance and appearance [55]. Robotics refers to the art and science of performing functions by an automatic system, device, or apparatus that appear to require human intellect [56]. Robotic teleoperation is a genre of teleoperation where a human operator communicates and supervises a robot over a communication channel, collects information regarding the remote environment, provides orders or suggestions related to task completion as a master, and the robot executes the task based on the control and feedback from the operator potentially assisted by varying levels of its own artificial intelligence [57]. Fig. 2 illustrates the basic concept of robotic teleoperation.

2.2. Teleoperation problem overview

To assist with complex task execution and for easier operation, a teleoperated robot may have various levels of autonomy. Based on the level of operator intervention and self-autonomy, the robotic platform may be called an autonomous robot or a teleoperated robot. Choi et al. [58] tried to explain the segregation of a teleoperated robot from an autonomous one using Fig. 3 demonstrating that in reality there is something of a continuum.

To support the scalability of operator intervention, different control techniques have been proposed, such as collaborative control [59], mixed-initiative control [60], adjustable autonomy [61], and sliding autonomy [62] amongst other techniques. However, all of these control mechanisms are negatively affected by time-varying control input delay and intermittent communication. Incomplete situational awareness along with the delay and or intermittent communication can detach a teleoperated robot from the operator.

Lag, latency, or command delay is the time delay between command input and visible output response. Delay or latency is caused due to the time taken to transfer data or information across a communication channel [63]. Latency starts affecting teleoperator perception from as low as 10–20 milliseconds [64]. If it starts increasing beyond this, it can significantly impact the teleoperator's performance [65]. If the latency increases from 8.3 to 225 ms, teleoperator reaction time increases by 64%, and error rate increases by 214% [63]. Some studies (such as [66,67]) claim a teleoperator's pursuit tracking performance can be compromised, and controlled manipulation becomes nearly impossible if the latency reaches 300 to 320 ms [68]. While driving at reasonable ground speeds up to 90 km/h, vehicle control has been shown to degrade significantly once latencies exceed 170 ms [69].

Variable latency, or jitter, can be even more problematic for the control of a remote robotic system. For a situation of variable latency, if the standard deviation of the latency is more than 82 ms, the control over a robot has been shown to degrade significantly for placement tasks that require high levels of visual feedback [70]. For remote UGVs, UAVs and ROVs operated at reasonable ground speeds, time-varying delays cause a human operator to issue repeated commands and over-correct the steering and eventually lead to highly undesirable oscillations and potential loss of control [71,72]. This over-correction can make obstacle avoidance difficult for high speed robotic vehicles and result in latency damage to the robot in challenging environments.

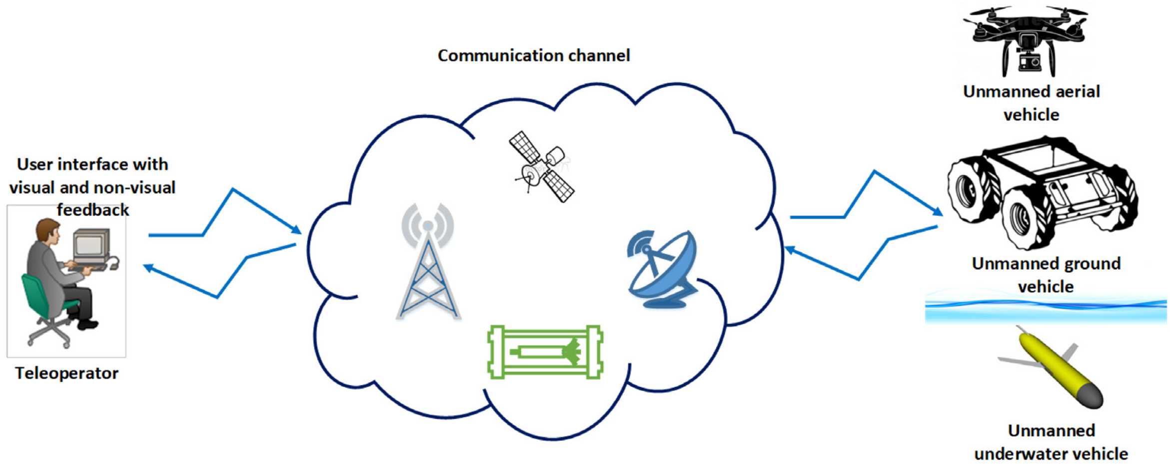

Fig. 2. Schematic diagram of robotic teleoperation. Teleoperators communicate with mobile robots such as UAVs, UGVs, and ROVs through communication channels such as radio links, satellite connections, cellular networks, and wired, and or wireless Internet connections. Teleoperators provide commands and receive visual and non-visual feedback via a user interface.

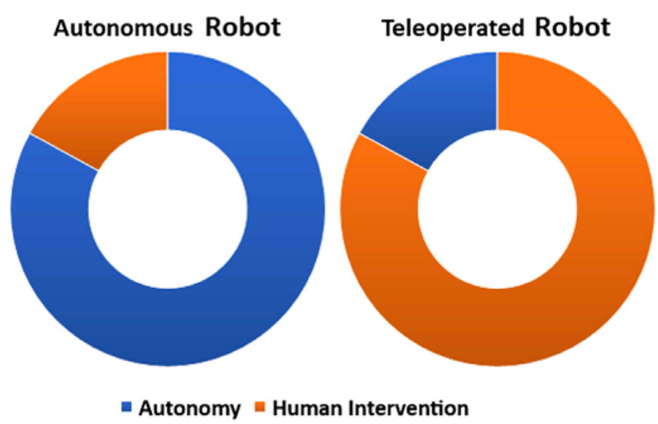

Fig. 3. Classifying robots using an autonomy and human intervention spectrum.
Source: Concept taken from [58].

Incidents of teleoperators experiencing motion sickness have also been reported due to teleoperation latency [73]. Additionally, intermittency on a communications link can further degrade the controllability of ground robots.

3. Teleoperated mobile robots

From a remote environment and robotic mobility perspective, teleoperated robots can be categorised into four types: teleoperation of stationary manipulators, ground robotic vehicles, aerial robotic vehicles, and underwater robotic vehicles. Considering the challenges involved in the teleoperation of robotic vehicles arising from latency, situational awareness limitations, bandwidth constraints, and control issues, we have narrowed the focus of this review to the three mobile robot vehicle types, their teleoperation methods, and teleoperation enhancement techniques. Similar teleoperation enhancement techniques can be implemented for stationary manipulator systems, however, including discussions relating to stationary manipulators would significantly increase the size of this paper. As a result, manipulators are not discussed.

3.1. Ground vehicles

Teleoperated ground vehicles are predominantly used in surveillance and reconnaissance. Therefore, research for UGV teleoperation techniques is heavily supported by military bodies around the world [74]. Based on the purpose and usage, teleoperated ground vehicles can be classified into three categories: unmanned ground vehicles, exploration rovers, and hazardous duty and search and rescue robots [13]. A history of teleoperated ground vehicle development efforts can be found in [75].

3.2. Aerial robotic vehicles

Teleoperated aerial robotic vehicles, commonly known as drones, are aircraft that can be controlled by a human teleoperator with greater or lesser levels of autonomy [76]. In recent times, there has been a sharp growth in the application of UAVs [77]. They are being used in surveillance [78,79], 2D and 3D mapping [80,81], agriculture [82], search and rescue [83,84], military applications [85], mining [86], and many more.

UAV research, development, and application is a significantly large research domain considering its widespread usage. Based on construction, shape, features, usage, and characteristics, UAVs can be categorised into many different types. However, this paper is focused on the teleoperation aspect of mobile robots. Therefore, we will discuss only the categorisation of teleoperation systems of UAVs. Other aspects of UAV characteristics and applications can be found in survey papers such as [87] (applications and research challenges), [77] (aerial manipulation systems), [88] (UAVs used for traffic monitoring), [7] (survey on Quadrator UAVs), [89] (survey on hybrid UAVs), [90] (survey on collision avoidance techniques for UAVs), [91] (survey on swarms), [92] (usage of game theories in UAV operation).

3.3. Underwater robotic vehicles

Vehicles that operate underwater, without a pilot onboard, and are able to perform an assigned task either autonomously or via teleoperation are called unmanned underwater vehicles (UUV) or underwater robotic vehicles (URV) [93]. Based on the mode of operation, UUVs are divided into two categories: autonomous underwater vehicle (AUV) and remotely operated underwater vehicle (ROUV) or often referred to as ROVs [94,95]. In general, ROVs are smaller in size, have limited propulsion power, and operate in shallow water [96]. Based on their applications, ROVs can be categorised into observation class, working-class, and special-use [97,98]. Based on the method of communication during teleoperation, ROVs can be divided into two types: Direct teleoperation ROVs and Mixed medium teleoperation ROVs. Fig. 4

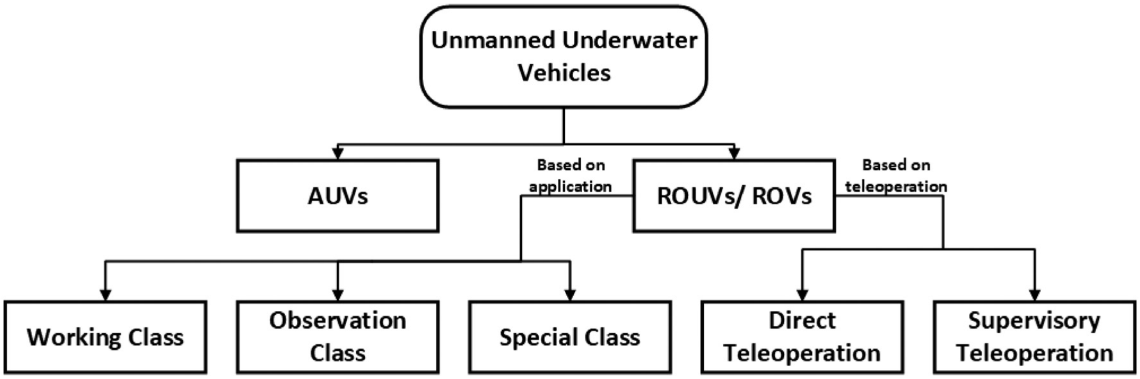

Fig. 4. Types of underwater unmanned vehicles.

provides a classification of unmanned underwater vehicles. As this paper is focused on teleoperation, this section of the paper will only discuss and provide examples of direct teleoperation and mixed teleoperation of ROVs.

4. Teleoperation methods

According to the mode of control teleoperation methods can be categorised into three principal types, namely direct teleoperation, supervisory teleoperation, and multimodal teleoperation [13]. Each of these is briefly introduced and explained in the following sections.

In this paper, we have further divided and described ground vehicle teleoperation systems into three categories: single vehicle systems, UAV supported systems, and multi-vehicle systems. In the single ground vehicle systems, teleoperators solely focus on a single-vehicle irrespective of the mode of the teleoperation. In UAV supported systems, additional assistance to either the ground vehicle or to the teleoperator is provided via a UAV. Finally, multi-vehicle teleoperation systems facilitate teleoperation of multiple UGVs by one or more than one teleoperator in a synchronised way. Several examples of these systems are included in the below discussions.

4.1. Direct teleoperation

In the direct control mode, teleoperators rely on visual feedback transmitted from the remote vehicle and provide control input using traditional controllers (e.g. joysticks or steering wheels). Direct control mode is also referred to as forced control mode or master–slave control mode. The overwhelming majority of teleoperation techniques are based on the direct teleoperation principle. Some recent examples of direct teleoperation systems are discussed in the following sections. As there are a large number of papers that have investigated different aspects of direct teleoperation, we have divided them into three different subsections, direct teleoperation of UGVs, UAVs, and ROVs.

4.1.1. Direct teleoperation of UGVs

Ground vehicles that are operated through direct teleoperation mode are mostly smaller in size and shape, and lighter in weight. A large number of the recent reports of teleoperating UGVs through direct teleoperation are short distance teleoperation and widely used in urban search and rescue situations (USRRs) or specially designed for military purposes (MSRRs). Radio-frequency is used for these short-distance search and rescue robots [99–101]. Some of the direct teleoperated robots described are claimed to be semi-autonomous, however, the robotic vehicles themselves do not offer any autonomy other than some additional sensors (such as smoke, gas, humidity, wind, water, temperature, PIR, etc.) [99,101]. In direct teleoperated UGVs, the teleoperation control decision is taken based on the situational awareness that can be achieved through video cameras only. Using multiple radio frequency channels to transfer control commands and sensor feedback is also not uncommon [102]. Instead of RF communication link, in some cases Bluetooth has been used in short distance UGV teleoperation [103] as well. A combination of RF and Bluetooth can enhance the reliability of the teleoperation for short distance operations [100]. Similar to underwater robot operation where an umbilical cord is generally used, an option for tethered operation can help ensure integrity of data and power transfer to UGVs for short distance but long duration operations [104]. [104] facilitated the docking and undocking to the tether remotely by the operator with the help of a camera located inside the robot. Besides the conventional line of sight (LOS) operation, and remote control GUIs, Android apps and web based user interfaces can provide more flexible direct teleoperation through mobile phones [100,103,105]. Direct teleoperation can be implemented for low-bandwidth and high-latency UGV systems. However, additional teleoperation enhancement techniques are vital for these scenarios [106]. For better wireless network connectivity a combination of directional and omnidirectional antennas can be used for longer distance direct UGV teleoperation [107,108].

4.1.2. Direct teleoperation of UAVs

Similar to UGVs, short distance UAV teleoperations are the most common type of direct UAV teleoperation, where the operators fly lighter UAVs or drones within line of sight. Short distance UAV teleoperation may or may not have video feedback from the drone. For conventional communication and transmission systems for UAV teleoperation, RF has been used frequently. The most popular data communication links for short-distance direct UAV teleoperation are 2.4 GHz and 900 MHz, which facilitates no more than two kilometres range for line-of-sight teleoperation [109].

For long-range UAV teleoperation, high-gain antennas, antenna trackers [109], satellite links, or long-distance cellular networks are required. Similar to other robotic vehicles, for long-distance UAV teleoperation, the UAV communicates with the ground control station (GCS), and the teleoperator provides their feedback to the GCS. A demonstration of cellphone-based long-distance UAV teleoperation with a user interface can be found in [109]. For extended-distance teleoperation, multi-hop global system for mobile communication (GSM) can be utilised for UAV direct teleoperation [110]. Both the 3G [111] and 4G [112] LTE GSM networks have been tested for long-distance teleoperation of UAVs. A schematic diagram is presented in Fig. 5 [109] that represents the cellular network-based long-distance direct teleoperation of UAVs. The cellular model supports both mobile phones as

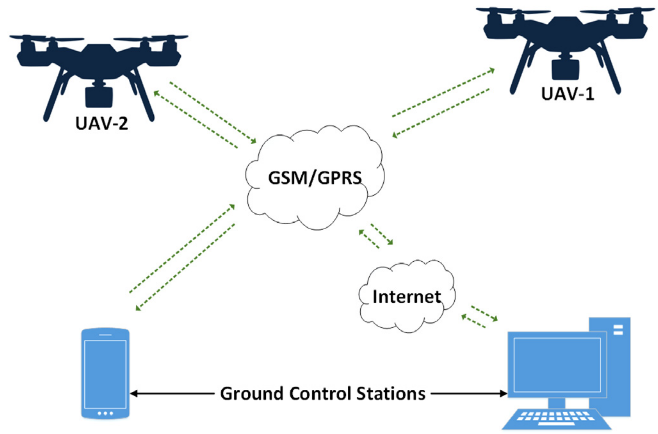

Fig. 5. GSM based teleoperation of UAV described by Solidakis et al. [109].

well as computers as the GCS and a user interface. For a PC based user interface, the GCS sends commands to the UAV through the Internet using the GPRS network. Simulation of satellite communication for long-range UAV teleoperation has been reported in [113].

The long-range teleoperation of UAVs has a huge potential for use in military applications. Therefore, there is little to no doubt that the research in this field is significantly under-reported. What is clear, however, is that multi-hop cellular networks induce additional data processing time in each hop. Therefore, past a certain distance, the delay increases to the point where control of the UAV becomes very difficult. Therefore, additional teleoperation enhancement techniques are necessary to improve the controllability. These techniques are discussed in Section 5.

4.1.3. Direct teleoperation of ROVs

Direct or master–slave teleoperation is the traditional method of teleoperating ROVs by the research community. In this method, the operator is on-board a vessel that supports the ROV, and communication is established using a single communication medium (Fig. 6). In this teleoperation technique, the ROV sends an underwater video feed to the operator, and based on this feed, the operator commands the ROV directly for movement and manipulation. The most common way to teleoperate an ROV directly is through the umbilical cord that transmits both power to the ROV and transfers data (command and video feedback) to and from the teleoperator. The operator's user interface is equipped with an industrial-grade personal computer, video feedback, joystick etc. Due to the use of an umbilical cord, direct teleoperation is mostly used for short distance teleoperation of ROVs. A number of approaches have used a similar technique for underwater ROV teleoperation. For detailed descriptions readers are referred to [96,114–119].

The concept of underwater wireless data transmission is not new [120,121] and has been used for data collection using underwater sensor networks. Thus far, sonar or acoustic communication links [122], visual light communication (VLC) [123], and underwater radio frequency transmission [124,125] have been studied for underwater communication and teleoperation purpose. However, the direct teleoperation of ROVs using these types of wireless links is more recent. In a very recent work Centelles et al. [126] described TWINBOT [127] and MERBOTS [128] where they used underwater acoustic links and radio frequency modems to teleoperate ROVs from a surface ship.

Although widely used, direct teleoperation using an umbilical cord limits the teleoperation distance of an ROV. Underwater wireless communication can extend range somewhat, but suffers from a number of limiting factors as well. An acoustic link has limited bandwidth (only a few kHz) and is prone to acoustic noise. It is also affected by multi-path phenomena caused by solid obstacles in the environment. Therefore, acoustic link-based teleoperation is also limited to relatively short-distance teleoperation only. VLC has higher bandwidth, however, water is a high attenuation medium for light and this again limits the range of teleoperation. Although RF is not affected by water quality and solid obstacles, the high salinity of seawater limits its range to only a few metres due to its high conductivity.

4.2. Supervisory teleoperation

Supervisory control is the technique where the teleoperator and the operated robot shares duty and control of the whole system. In this control mode, the operator performs a higher level of overall monitoring by receiving continuous feedback from the robotic vehicle, but intermittently providing control decisions [130,131]. In supervisory teleoperation, the robotic vehicle possesses artificial effectors and closes an autonomous control loop [131]. Supervisory control has been implemented in several ways for mobile robot teleoperation, an overview of these is provided in this section.

4.2.1. Collision avoidance and automatic tracking

A common way of establishing supervisory control is to include some level of local autonomy in the robotic vehicles. Obstacle detection and collision avoidance is a common capability of most of the semi-autonomous mobile robotic vehicles [132–135]. In recent years vision-based automatic object detection and tracking have added new dimensions and capabilities to the mobile robot teleoperation. Colour detection, morphological transformation, and feature selection techniques [136], and edge following and turning technology [137] automatically track paths using vision-based tracking algorithms, eliminating the need for the operators to worry about the moment to moment control of the mobile robots. Although primary developed for fully autonomous robots, Simultaneous Localisation and Mapping (SLAM) based path planning for a teleoperated mobile vehicle can offer a level of automatic tracking based supervisory control [138] as well. Other examples of vision-based leader tracking techniques are discussed under the leader–follower supervisory teleoperation model section.

4.2.2. Autopilot

Autopilot technology is another way of sharing control between the teleoperator and the robotic vehicle. In autopilot mode, the operator selects the point of destination/target and the robotic vehicle calculates the route and follows it autonomously. Autopilots have been implemented and tested for all the types of mobile robotic vehicles discussed so far. [139–144] describe autopilot (predefined flight path or way-point following) in single UAVs and UAV swarms. Description of autopilot systems for UGVs can be found in [106,145,146].

4.2.3. Leader–follower control

Another popular technique of supervisory control for multiple non-holonomic and distributed mobile robotic vehicles is the leader–follower method where each robotic vehicle is equipped with sensors such as laser, LiDAR, or camera to sense, compute, track, and establish peer-to-peer communication with a lead vehicle, or just follow GPS breadcrumbs. There are several formation control techniques of these non-holonomic leader–follower methods described in [147–150]. Examples of LiDAR-SLAM-based leader–follower techniques for all-UGV systems can be found

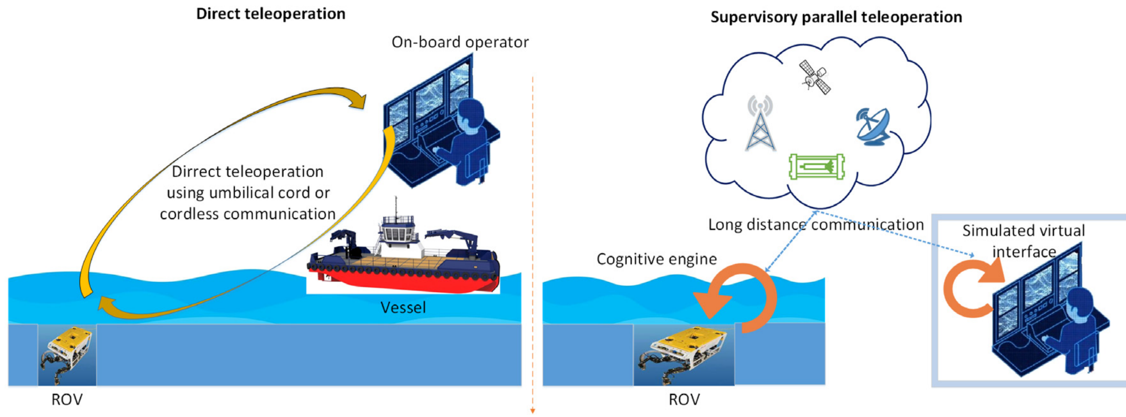

Fig. 6. Direct and mixed teleoperation of underwater robotic vehicles.
Source: Idea from [129].

in [138,151] where the leader having LiDAR, inertial measurement unit (IMU) and first-person view FPV camera is followed by multiple ground robots having an IMU and monocular camera to sense and maintain the relative distance from each other and the leader.

A team consisting of UGVs and UAVs can also be teleoperated easily by a leader–follower supervisory control mode. In the majority of the approaches described in the literature, the UAV follows the UGV using a downward-looking camera feed and vision-based automatic tracking technology and the UGV is directly operated by the operator [152–154]. UGVs following UAVs using a computer vision algorithm and a camera feed that is onboard the UGV and upwards looking is also not uncommon [155,156]. The major drawback of these techniques, however, is that the operator does not have any direct control over the follower robots. If the tracking system fails, which is common when operating in challenging environments, the overall UGV–UAV teleoperation system fails.

4.2.4. Swarm control technique

The study of multi-mobile robot systems has increased greatly in recent years. Multi-robot systems have proven their capacity for solving real-world problems over and above what is possible with single mobile robot systems. In the literature, a multi-UAV system with a large number of UAVs is referred to as a UAV-Swarm or Aerial-Swarm. Multi-UAV systems often consist of multiple smaller drones. The falling price of individual drones, improved processing hardware, better sensor networks, and smoother communication techniques has enabled and increased the efficiency of multi-UAV systems. Detailed multi-UAV system architectures can be found in [157,158]. Skorobogatov et al. [45] illustrated the applications of multi-UAV systems in their survey. Besides aerial swarms, UGV-swarms [159,160], and UAV–UGV–UMV (UMV—Unmanned Marine Vehicles) [161] are also popular in military and urban operations. Similar to other teleoperation types, multi-mobile robot systems also are teleoperated over wireless radio links, cellular networks or the Internet (long or short distance). Teleoperated swarms are controlled broadly in supervisory control mode. Additionally, they have formation control techniques to control the behaviour of multiple drones at the same time.

Some popular formation control techniques for swarms are: leader–follower technique [162,163], rigidity maintenance technique [164], real-time online leader selection and leader changing technique [165]. In these techniques, the leader is capable of detecting and resolving a deadlock configuration created either by the environment, follower formation, or operator command. The multiple agents are often coordinated by models of market economics. Therefore, this formation control technique is called "market economy". In this method, all the multi-robot teammates try to trade resources and tasks to increase the overall efficiency of the system and increase individual profit [166]. A survey of the multi-robot systems using an earlier version of the market economy technique can be found in [167]. Earlier approaches of market economy applications such as [168,169] used to tender based on time or distances. Later approaches such as [170] applied an energy consumption based bidding algorithm. Some further improvements of this market economy technique for multi-robot systems have been described in [171,172]. However, the market economy and auction method perform better in a system with perfect communication between all the agents. Therefore, it requires high communication bandwidth and coverage. Another major drawback of the market economy model is, if more than one agent of the system find and bid for a task at the same time, the market economy may fail. Moreover, for calculation and bidding, the robot agents require relatively high computation capability.

4.2.5. Multi-layer control

Multi-layered control is a supervised control technique where the total control of the system is divided and executed into more than one layer. Multi-layered control has mostly been used for multi-robot systems. Earlier approaches to teleoperation of multiple UAVs was described by Lee et al. [173], Franchi et al. [174], and Lee et al. [175]. They proposed a three-layer control method to teleoperate UAVs over a wireless Internet connection. In the first layer, each UAV follows and tracks its own kinematic Cartesian virtual point (VP). In the second layer, multiple VPs are controlled in a distributed manner where the VPs communicate only with their neighbouring VPs. Finally, on the third layer, the teleoperator controls some of the VPs, based on the haptic feedback of those VPs. In a similar time-frame, Franchi et al. [176] described a shared control technique for multi-robot teleoperation where the control is shared between task controller, obstacle controller, topological controller and the human operator.

4.2.6. Supervisory parallel control

Supervisory parallel control is a relatively newer paradigm. In this method, a virtual model of a mobile robot is simulated in the user interface, which could be located far away onshore. The environment of the virtual model is set according to the real remote environment, and the operator gives commands and sees feedback in the local VR loop. The mobile vehicle in a remote environment is controlled using a cognitive engine offshore. As both the operator and robotic systems are controlled using local parameters and variables, and no video feed or operator state is transferred, this method does not require a high bandwidth communication link.

Refs. [129,177] described supervisory parallel teleoperation of an ROV, where they used a task-parametrised hidden semi-Markov model (TP-HSMM) and a linear quadratic tracking (LQT) based integrator to represent the task, create a virtual model and generate motions. This probabilistic motion generation model learns from past learning. Ref. [178] used a satellite link for long-distance communication and a cognitive engine and task priority algorithms for their parallel supervisory control based teleoperation (Fig. 6). However, the tasks that require higher precision are not achievable as the operator performs the manoeuvres in a locally simulated environment, and the mobile robots execute in a different but similar environment using this parallel control. Moreover, this teleoperation method requires a highly skilled operator as there is no visual feed available.

4.3. Multimodal teleoperation control

Multimodal mode, also known as multi-sensory mode, collects and synthesises more than one sensor cue and provides a multimodal view of the world to the teleoperator [179]. For a dynamic and complex remote environment, making correct and timely control decisions could be difficult for a teleoperator. Control techniques with multi-sensor interfaces that can offer efficient control command generation tools along with rich situational awareness can cope with these difficulties. A large number of modern teleoperation examples reported in the literature uses multimodal control techniques. As multimodal sensor feedback is used to enhance teleoperation, a brief introduction to this approach is described here, but further elaboration and discussion is provided in Section 5.

Multimodal control mode with multi-sensory interface offers a variety of control options such as individual actuators, coordinated motions along with visual (i.e. video, image, text, immersive 3D experience) and non-visual (i.e. force and sound) feedback. Examples of multimodal teleoperation with vibrotactile feedback can be found in [110,180–189]. Further, examples of wearable gloves and hand gesture-based short distance UAV teleoperation includes [162,190–194]. In multimodal teleoperation, user interfaces combine feedback from multiple sensors and offer an integrated display of the remote environment such as virtual reality (VR), augmented reality (AR), or mixed reality (MR) amongst others. More detailed discussions are provided in Section 5.

4.4. Summary

Our analysis of the literature indicates that supervisory control is currently the most common control mechanism for teleoperation of mobile robots, followed by direct teleoperation, with multimodal approaches emerging, but not yet widely used. For complex and dynamic remote environments multimodal control provides multi-sensor interfaces and control input tools. Multimodal teleoperation control offers better situational awareness through integrated visual, tactile, and/or immersive interfaces. However, multimodality requires high computation and bandwidth capability, contributes to latency, and can increase cognitive workload. The simpler direct wired or wireless teleoperation approach is equally effective for UGVs, UAVs, and ROVs, although it is best suited to short-distance teleoperation. Besides direct line-of-sight operation, video feed-based teleoperation through remote control GUIs have been used as a means to provide situational awareness to teleoperators. Direct teleoperation is, however, less forgiving to latency, intermittency, data loss, and other communication issues than the multimodal or supervisory forms of teleoperation.

Supervisory control is continuing to develop, and has become the most common control mechanism for teleoperated mobile robots. For single mobile robot systems, the sharing of responsibilities between the robot and the operator can occur in the forms of obstacle detection, collision avoidance, automatic path planning and tracking, auto-piloting, or parallel control through a virtual robot simulation. For teleoperation of multiple mobile robots, the robots close an autonomous control loop through leader–follower or swarm formation control techniques. The sharing of responsibilities between the robot agent and the teleoperator can occur in multiple layers, where the robots have autonomy in lower layer tasks and, the teleoperator controls the robots through upper layer instructions. In the supervisory control technique, robots require a higher computation capability than the direct control robots. For multi-robot systems, coordination techniques such as market economy also require higher communication bandwidth. A relatively new supervisory control technique called supervisory parallel control tries to resolve these issues through the local virtual model and offshore cognitive engine, where the bandwidth requirements drop significantly and the robot agent does not require a high computation capability, although this comes at a cost in the form of lower precision and the requirement for a highly skilled teleoperator. This is, however, an active research area and new techniques to address these challenges continue to emerge.

5. Enhancement techniques

For more than half a century, the research community has worked towards resolving fundamental control problems underlying robotic teleoperation with and without time delay, over remote communication links [195]. As technology has advanced, teleoperated robots have become more integrated, and various approaches to enhance teleoperation have been attempted. This section of the paper provides a rigorous survey of these approaches based on a review of a wide range of journal and conference articles, project reports, theses, and book chapters published since 2000 in the area of teleoperation enhancement.

After a critical analysis of the reviewed publications, we have found that contemporary teleoperation enhancement research approaches can be classified into four principal categories. Researchers have investigated teleoperation enhancement based on one or more of the following approaches: operator perception enhancement, interface improvement, control system improvement, or latency compensation. Fig. 7 provides a taxonomy of all of the surveyed approaches. The subsequent sections provide details on each of these approaches.

5.1. Operator perception enhancement

In most teleoperation scenarios, perception of the remote environment is the principal medium through which control decisions made. Perception of space, environment, and motion helps to shape operator interaction and decision [196]. Better perception of the remote environment helps an operator to make better control decisions and hence enhances teleoperation performance. The research community has experimented on viewpoint shifting, automatic view adjustment and visual map area merging techniques to enhance the visual perception of the environment. Non-visual human senses such as audio, force and tactile senses have been used to offer additional information about the remote environment. In particular, the inclusion of vibro-tactile feedback to the teleoperation task can be considered a success in the teleoperation research community. The following subsections discusses recent work in the area of operator perception enhancement.

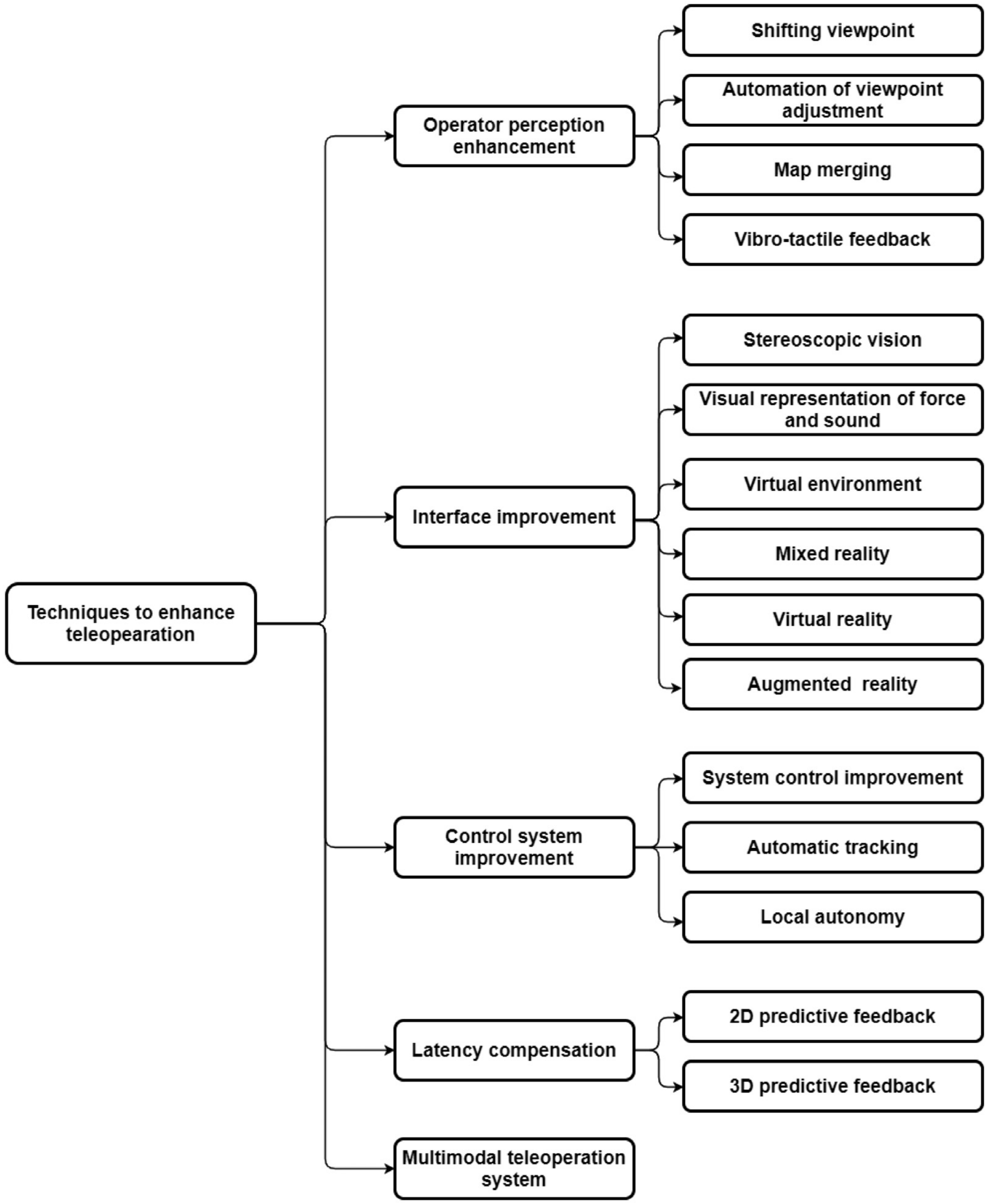

Fig. 7. Classification of teleoperation enhancement techniques.

5.1.1. *Shifting viewpoint*

In a conventional visual feed based teleoperation scenario, cameras or visual sensors are mounted to the remote mobile robot, which offers an egocentric view of the environment. Shifting to an exocentric view not only widens the field of view but can also offer additional information about the characteristics and situation of the mobile robot itself. An exocentric view in the user interface refers to a viewpoint that encompasses the robotic platform itself. In some literature the exocentric view is named the "third-person"view. It is a common practice when teleoperating robots to use onboard sensors and cameras for robotic vehicle control. The first-person or egocentric view achieved through the onboard cameras is generally sufficient in relatively easier terrains and environments. However, whenever obstacles and narrow passages need to be traversed in a challenging environment, the task of teleoperators can become difficult due to narrow fields of view [197,198]. This problem with onboard egocentric views is often referred to as "soda straw vision" [199].

Different types of techniques have been applied to achieve an exocentric view to enhance teleoperation for different robotic vehicles. A number of contemporary approaches notably [154,200], and [201] have used supplemental Micro Aerial Vehicles (MAVs) in addition to the teleoperated mobile robots to achieve an exocentric view and a wider environmental perception. However, adding additional airborne mobile robot units to the principal robots imposes further significant control and reliability challenges. The GPS-based co-localised system proposed in [200] along with feature-based autonomous detection of the principal mobile robot by a MAV for continuous localisation and exocentric view generation without requiring separate control steps can be used to resolve the control challenge. The use of a single controller (haptic) for all the mobile robots of the system has also proved a helpful approach to resolve the control challenge [201]. Modification and implementation of UAV swarm control to incorporate other mobile robot types can make it relatively easy to achieve exocentric viewpoints for UGV–UAV, UAV–UAV, or even AUV–UAV systems [202].

Other techniques to achieve an exocentric view to enhance teleoperation include using multiple cameras, vehicle body mounted cameras, and overhead cameras. Hughes et al. [203] decoupled camera control (direction of gaze) from the UGV (direction of travel). Keyes et al. [204] experimented with the impacts of multiple camera-feeds and overhead camera feeds over an egocentric camera feed. Sun et al. [205] used multiple cameras as well as an additional body mounted camera to visualise the vehicle itself to provide the feel of an exocentric view to an operator.

Adding additional overhead cameras, however, limits the usability of mobile robots, especially in search and rescue situations when the robot needs to operate within a congested environment. In an attempt to overcome this, there has been research done to achieve an exocentric view without the help of overhead cameras or additional robots, to enable robotic vehicles to deal with congested spaces and spatial limitations. Using multiple first-person view images to render a bird's eye view [206] is one idea that has been proposed. Sato et al. [206] described an approach where the first-person images were captured by fish-eye cameras attached to a UGV and homography transformation was performed prior to stitching them together. However, stitching still images comes with its shortcomings as well. It is difficult to comprehend the perception of distance from a third-person view generated from such images. Integrating depth sensors to measure the distance to an obstacle [207], or using a laser range finder along with multiple fish-eye cameras to create an exocentric view incorporating obstacle distance perception [208] can work effectively to overcome these shortcomings.

5.1.2. Automation of viewpoint adjustment

Besides achieving a wider exocentric view, our survey of the literature suggests that perception enhancement can also be achieved by changing the point of view from a fixed viewpoint to a flexible one where the required viewing direction is automatically anticipated and adjusted. In this way, enhancement of teleoperation can be achieved through automation of the camera viewpoint. In a conventional teleoperation situation, the camera view is fixed based on the principal direction of navigation, however this fixed viewpoint limits situational awareness for the teleoperator. Situational awareness can be improved by decoupling camera feeds from vehicle direction [203]. However, if the teleoperator needs to manually operate the camera separately, this reduces their focus on remote vehicle control and navigation [209]. Automation of the optimal positioning of the mobile robot mounted camera can resolve this issue. Rahnamaei and Sirouspour [209] have proposed an algorithm to automate the optimal positioning of a single camera for a remotely operated UGV. Based on the surrounding environment and task circumstances, their algorithm adjusts the onboard camera view continuously. The use of head tracking technology to adjust and automate the remote camera viewpoint has also been explored with some success [210,211].

5.1.3. Map merging

Achieving an exocentric view, or automatic adjustment of the viewpoint of a single mobile robot or a multi-robot system still does not enable comprehension and mapping of an environment in its entirety, as real-world environments often consist of sections underneath overhangs or inside caves. Merging the visual information collected by one or multiple mobile robots together to achieve a more complete awareness of the environment has been described by several researchers as a possible solution to this problem. Sujit and Beard [212] used multiple UAVs to map an area as a 2.5D environment and merged these to prepare a complete map. Bircher et al. [213] tried to map a 3D environment through a single UAV using a next-best-view approach. While map merging implemented in a single UAV system or a UAV swarm has been shown to be effective, air–ground exploration through UAV–UGV coordination and merging the maps generated by the UGV and UAV individually, have the ability to provide the operator with a more comprehensive understanding of the environment. Map merging can also be effective for better situational awareness in a submerged environment. The use of long-term mapping techniques or implementation of SLAM approaches for underwater ship hull and pipeline inspection or bathymetry mapping has also demonstrated the effectiveness of these techniques in underwater teleoperation scenarios [214,215]. Although map merging enhances situational awareness, the merging process can be frustratingly slow and often hampers teleoperation. As a result, map merging techniques are often used for generating maps that are to be used offline. To overcome this limitation, techniques such as the offset accounting algorithm [216,217] or brute force matching techniques [218] have been used to generate a better live 3D map that can provide the operator with a coordinated 3D situational awareness for real-time mobile robot teleoperation (see Table 2).

5.1.4. Vibro-tactile feedback

Although vibro-tactile interfaces could be classified and discussed under the interface improvement section (Section 5.2), the use of haptic feedback offers a non-visual form of information that can enhance the perception of the remote environment. An effective way of better realising the remote world is to apply multimodal interfaces and leverage on more than one human sensory organ. Besides the human visual sense, the tactile sense is an effective complement to perception [221]. Therefore, we have made the decision to include discussion relating to the teleoperation approaches that use vibro-tactile feedback under the operator perception enhancement category. Several approaches have tested the possibility of using vibro-tactile devices to aid robotic teleoperations. Some of these are detailed below.

Haptic devices are gaining popularity in fields such as gaming and entertainment. However, the initial implementation of haptic technology was borrowed from a haptic device developed for space exploration. Ryu and Kim [187] used POS.T wear, a set of vibration devices designed by Yang et al. [222] that was custom built for space exploration. POS.T wear is capable of providing vibration feedback to the whole body of the teleoperator. The experiment showed a better situational awareness was achieved with 3D sound feedback with a head-mounted display rendered in stereo. A similar technique has been used and validated by De Barros et al. [223] through a map sketching task in a teleoperation scenario. After the initial success, several approaches have thus far incorporated haptic devices to enhance teleoperation through vibro-tactile feedback for ground robotic vehicles. Lee et al. [220], Melchiorri [188], Casqueiro et al. [181], have used haptic devices to receive vibrotactile feedback along with a visual feed. Various control techniques have been adopted by these approaches to make the best out of force feedback. Passivity preservation of the system was ensured in [188], an event-based control technique is proposed in [184] to minimise the effect of system delay and ensure real-time force feedback, and anti-collision local autonomy was implemented in [181].

For UAV teleoperation, the application of a haptic feedback based master–slave control technique was initiated by Stramigioli et al. [219]. AbdElHamid and Zong [110] used a multi-axis rotating device to add additional motion feedback with a virtual interface for GSM-based long-distance UAV teleoperation. In recent times, for line of sight (LoS) UAV teleoperation, hand-worn

Table 2
Summary of operator perception enhancement techniques.

Author (Year) [Ref.]	Technique	Medium	Robot type
Shifting viewpoint			
Komatsu et al. (2020) [208]	Multiple fish-eye camera images with laser range finder to generate view	–	UGV
Gawel et al. (2018) [200]	Video feed from micro aerial vehicle	Wifi	UGV–UAV
Awashima et al. (2017) [207]	Multiple fish-eye camera image rendered into bird's–eye view	–	UGV
Claret et al. (2016) [201]	Coupled free flying camera on a single haptic controller	Internet	Manipulator-UAV
Sato et al. (2013) [206]	Multiple image rendering to generate bird's–eye view	–	UGV
Keyes et al. (2006) [204]	Overhead camera mounted on UGV	IPC wireless	
Hughes et al. (2003) [203]	Exocentric view by decoupled and multiple camera views	–	UGV
Automation of viewpoint adjustment			
Rahnamaei and Sirouspour (2014) [209]	Continuous camera adjustment algorithm based on remote task environment	Internet	Mobile robot
Fournier et al. (2011) [210]	Immersive chamber (CAVE) based virtual environment that facilitate 360 view of the remote environment	Internet	Gazebo robot simulator
Zhu et al. (2011) [211]	Operators eye gaze and head motion based camera view adjustment	–	Modelled rock breaker
3D map merging			
Jha et al. (2020) [218]	Merging 2D map from UGV and 3D map from UAV through brute force matching technique	WiFi	UAV–UGV
Butzke et al. (2015) [217]; Michael et al. (2014) [216]	Using map-merging algorithms to create 3D maps generated by a UGV and a UAV	WiFi	UGV–UAV
Vibro-tactile feedback			
Macchini et al. (2020) [190]	Hand-worn haptic glove with six tactors	Radio Link	UAV
Zhang et al. (2020) [180]	Haptic feedback controlled by CBF functions to reduce error	–	UAV
Casqueiro et al. (2016) [181]	Vibration feedback with anticollision	–	Holonomic ground vehicle
AbdElHamid and Zong (2015) [110]	Multiple axis rotating device for motion feedback	Cellular network	UAV
Shahzad and Roth (2014) [184]	Event based controller with force feedback	Internet	AutoMerlin
Ha and Lee (2013) [152]	Haptic feedback using PSPM to maintain stability in imperfect communication	Internet	UAV–UGV
Stramigioli et al. (2010) [219]	Vibro-tactile feedback with direct master–slave control	–	UAV
Lee et al. (2006) [173,175,220]	Haptic joystic to enhance awareness	–	Wheeled robot
Ryu and Kim (2004) [187]	Vibration feedback for teleoperators whole body along with 3D sound	–	–
Diolaiti and Melchiorri (2003) [188]	Computation and providing virtual interaction force based on the obstacle	LAN	Wheeled robot

glove based controls are gaining popularity. Macchini et al. [190] designed a hand-worn haptic glove to operate an LoS drone. Ha and Lee [152] incorporated haptic feedback in a vision-based UAV–UGV system. To bring stability and keep the vibration feedback as close as possible to the input signal, techniques such as control barrier function (CBF) [180], and passive set-position modulation (PSPM) has also been investigated [110].

In conjunction with other feedback types, both visual and non-visual, vibro-tactile responses to the teleoperator can increase situational awareness and help to achieve better teleoperation performance. However, most of the methods described above have not considered the significance of time-delay in the data transmission process, and their utility is likely to be significantly impaired once the latency passes a certain threshold.

5.2. Interface improvement

Robotic teleoperation interface design is a major field of research. A significant amount of work has been done to improve interfaces in an attempt to enhance teleoperation. Several recent survey works have also been completed that describe the interfaces for field robotics [53], the basic user interface design guideline [52], the social and psychological techniques for teleoperation interface design [51], and different data visualisation techniques for teleoperation interface design [48]. In this section we have categorised the most common interface design approaches we have identified into broad categories according to the methods through which they aim to enhance teleoperation.

5.2.1. Stereoscopic vision

In neuroscience, the capability to register a 3D scene based on visual input from two visual sensing organs is called stereoscopic vision [225]. Stereoscopic vision systems are capable of providing the user with better perception and understanding of an environment through depth estimation. There are some approaches in mobile robot teleoperation interface design that utilise a stereoscopic vision system to enhance teleoperation. Martins and Ventura [226] and Kratz et al. [227] used stereo camera for teleoperation of ground vehicles. Both of these approaches used head-mounted display device (HMD) and head tracker technology to offer an immersive experience to the operator. Both the studies claim that the stereo HMD systems enhanced teleoperation by providing depth perception. Although stereoscopic systems provide an almost 3D depth estimation and perception capacity, these systems are prone to image misalignment. Stereo systems with HMDs often create too much irrelevant information in a short period of time that can increase cognitive workload, as well as increasing communication channel bandwidth requirements.

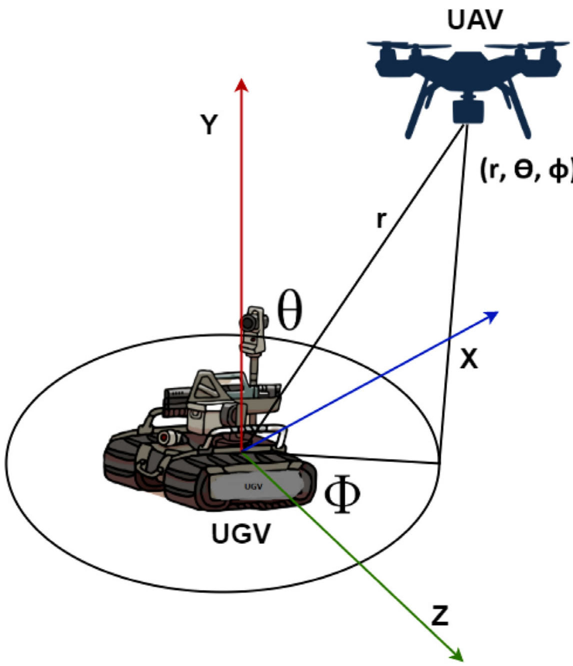

Fig. 8. Schematic diagram of UAV–UGV coordination proposed by Saakes et al. [224] to achieve an exocentric view to enhance teleoperation, where a spherical coordinate system was used to track position and orientation.

5.2.2. Visual representations of force and sound

Sound localisation and force sensing have become accepted as new modalities for enhanced situational awareness in interface improvement research. Commonly, advanced and specialised robotic platforms use these types of information for advanced localisation and navigation tasks through tools such as haptic devices [228], 'ManyEars' [229] and 'HARK' [230,231]. These tools offer robotic task execution capability improvement, but limited enhancement in teleoperation. 3D visual representation of sound and force in the same conventional user interface can, however, increase the situational awareness of the teleoperator and enhance teleoperation performance. To demonstrate [232] designed a 3D user interface that added and represented forces as bar graphs and arrows of varying colours and sizes based on their intensity. Sound positions were represented through ring bubbles. Fig. 9 shows how representations of sound and force appear in 3D shapes. A physical teleoperator survey [232] suggested that their technique provides some enhancement to teleoperation performance.

5.2.3. Virtual environment

A virtual environment is a networked common operating space that permits users to interact with the computed state of a physical environment. For robotic teleoperation, a virtual environment helps to create a psychological state in which teleoperators can identify themselves as present in the virtual environment [234]. This psychological state is also known as immersive reality. Video gaming interfaces that use particular devices like joysticks and steering wheels can be argued to produce a form of virtual reality. However, these interfaces lack additional feedback, such as motion and vibration, amongst others, intended to provide operators with enough information to sense and feel the environment. Research works that describe a physical system to create a remote environment and offer a better immersive experience and enhance situational awareness are described in this section, which, it should be noted, is different from conventional VR technology.

For mobile vehicle teleoperation, only a small number of approaches have been identified that described virtual environment creation to enhance teleoperation. [235] built a prototype of a 2D virtual environment system using a haptic workstation with a joystick, steering wheel, and a 2D virtual screen display that tried to create a realistic virtual environment through visual and haptic feedback. A better example of virtual environment design is 'caddie paradigm' presented by Lemoine et al. [232] in which a treadmill is used as their free-locomotion interface. In this prototype, a teleoperator could control the robotic platform by walking and pushing the treadmill based on a virtual representation, where the visual feedback was displayed on a sizeable 2D projection screen. Fig. 10 represents the virtual environment system using a treadmill. Creating a virtual environment for mobile robotic vehicles is sensitive to location, environment, and robot type. A virtual environment created for a specific scenario may not be easily transferable to another. The later designed immersive interfaces such as mixed reality (MR), virtual reality (VR), and augmented reality (AR) are more easily transferable.

5.2.4. Virtual reality

Virtual Reality (VR) can be described as the reconstructed or simulated experience of an environment that may or may not represent the real physical world in an accurately simulated form [236]. VR has the capability of immersing a teleoperator into the environment of a robotic platform with high perceptional awareness. Augmented reality and mixed reality are also types of virtual reality. Teleoperation enhancement through augmented and mixed reality are described under the corresponding headings later in this section.

Among teleoperation approaches for mobile robotic vehicles, VR has been primarily achieved through two different techniques: by 3D reconstruction of an environment from sensor feedback, and using off-the-shelf commercial VR technology and gaming tools. Huber et al. [237] and Mostefa et al. [238] described models for teleoperation interface to generate realistic 3D environment in real-time from sensor feedback. [237] utilised a video camera and laser scanner and [238] only used a video camera feed for the reconstruction. In [210], to create an immersive virtual environment, the authors used a cave automatic virtual environment (CAVE) chamber. The authors used 'OpenGL 'architecture and the 'OpenSceneGraph' 3D toolkit to generate the immersive human centric virtual reality.

Most of the reported studies that attempted to enhance teleoperator perception through the use of virtual reality, used off-the-shelf commercial VR technology and gaming tools. Refs. [113,210,239,240] used head-mounted device (HMD) VR sets with IMUs to control the mobile robot via the teleoperator's body posture. Refs. [126,241] used commercial VR equipment such as the HTC Vive and Oculus Rift headsets, and UWSim [242] for provision of the VR experience to the operators.

3D VR enhances performance for teleoperations as the VR feedback provides them with 3D perception and better awareness of the remote environments while the head tracker can be used to automatically adjust both the camera viewpoint and robot direction. The latest VR technology does not need to calculate and construct the 3D environment, as the headset with a pair of independent video streams utilises the operator's eyes and brain to create the depth perception. Accordingly, complicated and time-consuming calculations are not necessary. Moreover, virtual reality is transferable for all mobile robot types (i.e. UGVs, UAVs, and ROVs). However, significant research is still required to offer predictive 3D reconstruction in the VR interfaces in order to reduce the impacts of latency, which can be worsened due to the higher demands from transmitting a stereoscopic video feed or from additional re-processing requirements required in order to generate an immersive view within a VR headset (see Table 3).

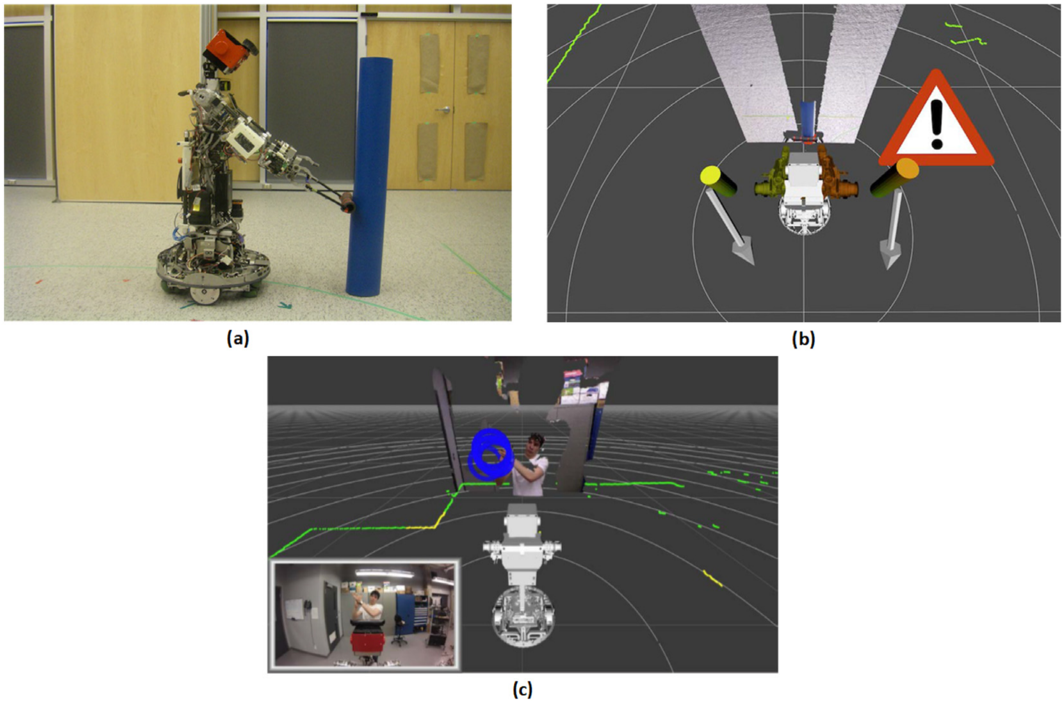

Fig. 9. (a) Teleoperated ground vehicle sensing obstacle through force feedback, (b) representing forces in 3D shapes, and (c) sensing and representing sounds as ring bubbles.
Source: Taken from [233].

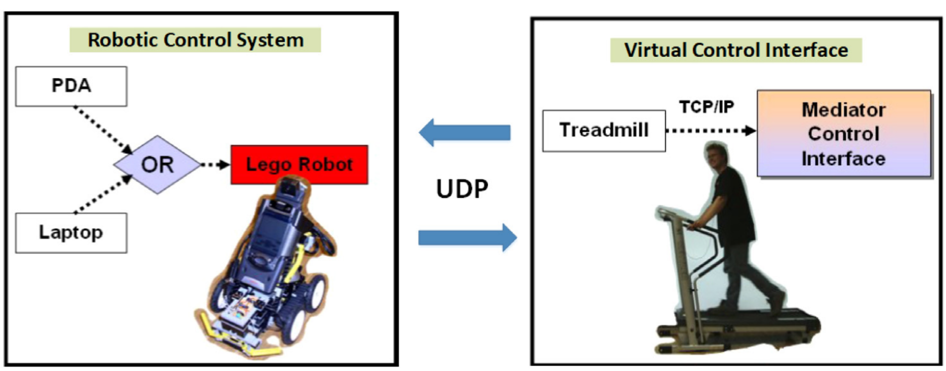

Fig. 10. Representation of Caddie paradigm: a 2D feedback-based virtual reality system.
Source: Taken from [232].

5.2.5. Augmented reality

Augmented reality (AR) can be described as a form of interactive experience where virtual information can be overlaid with the real-world using computer-generated enhanced perceptual information [247,258]. A conventional AR presents three features: (a) it facilitates real-time interaction, (b) it combines the virtual world with the real-world, and (c) it provides 3D registrations of the virtual world [259]. AR has been used in aspects of learning and teaching, for mobile telecommunications, in video games, and in other areas [260–262].

There are many approaches that use AR to enhance teleoperation as it can improve communication between robots and operators through intuitive visual and spatial dialogue. Several papers [246,247] described image activated AR generation techniques as an aid to enhance teleoperation by offering additional situational awareness. Rodríguez et al. [247] created AR through activated turn direction arrows. When activated, their AR user interface is capable of detecting specific labels that trigger superimposed virtual arrows (Fig. 11). Vozar and Tilbury [246] have used a similar image activated AR generation technique through a crosshair in the user interface, activated when placed on an object, providing a 3D green or red shape based on its

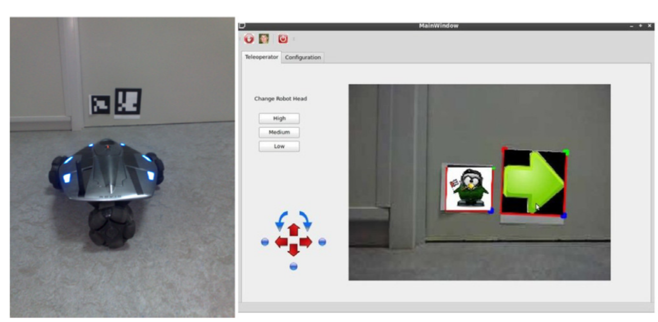

Fig. 11. Teleoperated robot in its environment, and the corresponding AR-based user interface.
Source: Taken from [247].

Table 3
Summary of interface improvement techniques.

Author (Year) [Ref.]	Technique	Medium	Robot type
Stereoscopic vision			
Kratz et al. (2015) [227]	Head tracked stereoscopic video	WiFi	UGV
Martins and Ventura (2009) [226]	Stereoscopic vision on HMD by Onboard stereo camera	Wireless	SAR robot
Visual representation of force and sound			
Reveleau et al. (2015) [233]	3D representation of sounds and force in 3D user interface	ROS local network	IRL-1 telerobot
Virtual environment			
Lemoine et al. (2005) [232]	Treadmill with 2D screen based virtual representation	Wireless	UGV
Gutierrez et al. (2004) [235]	Operator virtual cockpit (Haptic Workstation) feedback and a 2D display	Internet, WiFi	UGV
Virtual reality			
De la Cruz et al. (2020) [241]	Applying HTC Vive and Oculus Rift based commercial VR HRI	Multimodal (RF/VLC/Acoustics)	ROV
Centelles et al. (2020) [126]	VR achieved using UWSim-NET window to operate twin ROV	Multimodal (RF/VLC/Acoustics)	ROV
Prexl (2017) [113]	Environment and predictive modelling with VR through HTC Vive	Satellite	UAV
Almeida et al. (2017) [239]	Immersive VR using body intension algorithms and HMD	Wireless network	Telepresence Robot
Mostefa et al. (2015) [238]	P3T Pioneer VR simulator based on Unity 3D game engine	Internet	Pioneer 3AT
Martins et al. (2015) [240]	VR based on HMD of 3-DOF head tracker	Wireless link	RAPOSA
Fournier et al. (2011) [210]	OpenGL and OpenSceneGraph based 3D immersive chamber VR	TCP/IP link	Pioneer 2DX
Huber et al. (2009) [237]	Exocentric 3D model of the environment using laser scanner and video camera	Wireless link	Gator and Land Tamer-2 platform
Augmented reality			
Fuste et al. (2020) [243]	Augmented reality motion interface by Reality Editor	–	AGV
Laranjeira et al. (2020) [244]	Additional data overlay from several sensor sources on a VR head set	–	ROV
Okura et al. (2013) [245]	Super-imposing a 3D model of the robot to a constructed free view scene	–	UGV
Vozar and Tilbury (2012) [246]	Virtual AR crosshair that changes colour based on the distance from UGV inside a VR workspace	–	UGV
Rodriguez et al. (2011) [247]	AR interface activated through turn direction arrow	Radio Link	Rovio
Collett and Macdonald (2010) [248]	AR vision by see-through HMD that display robot environment with additional 2D and 3D elements	–	UGV
Mixed reality			
Wojtkowski et al. (2020) [249]	DrEAM metaphore using CAVE-like virtual representation	–	UAV
Wu et al. (2020) [250]	Wearable Hololens interface with path, map, control command and virtual robot model	Internet	OMR
Chouiten et al. (2014 ,2012) [251,252]	A 3D virtual model of an ROV added to the egocentric video feed	Internet	ROV
Wang and Zhu (2011) [253]	2D video feed and 3D laser scanned feed	–	–
Labonte et al. (2010) [254]	Egocentric 2D video feed with 3D model of environment	Internet	Telerobot
Ferland et al. (2009) [255]	Laser based exocentric 3D mesh and 2D egocentric video feed	Wireless internet	Differential drive robot
Zeiger et al. (2009) [256]	Inter-changeable 2D and 3D view user interface	Internet	MERLIN
Nielsen et al. (2007) [199]	3D interface combining 2D video, 3D map and robot pose information	–	USARSim simulator
Sugimoto et al. (2005) [257]	3D UGV model superimposed in a scene created by stitching past and present frames	Radio link	Tokyo Mauri M1A2

distance from the robot arm. In this scenario, the operator can even get additional information about the geometry of the box.

Another important AR technique that has been utilised in the teleoperation research area is the superimposing of multi-modal interfaces together (superimposing a virtual indicator on a stereoscopic video [263], superimposing the 3D model of a robot onto a reconstructed scene [245], and superimposing multiple sensor inputs [244]). Other mention of AR integration includes multimodal user interface with AR by [264], and a laser scanner powered AR interface [243].

AR has the capability of providing additional information about the geometry of a target object. Most applied AR techniques used image-based object detection to trigger the augmented reality. However, in a new and challenging environment, such as a search and rescue situation, these techniques would be ineffective. AR does not attempt to reduce communication latency. Moreover, AR increases the burden of calculation and may increase the visual delay of the system. For particular objects in a scene, AR provides 3D perception, where the rest of the scene lacks the depth information that is present in the virtual reality view.

5.2.6. Mixed reality

When the virtual world and real world merge and physical and digital objects coexist to produce a visual environment, it is referred to as mixed reality. Accordingly, mixed reality is composed of augmented reality and augmented virtuality by using immersive techniques [265]. As mixed reality combines a real environment with the virtual information on a single interface, it can improve situational awareness for robotic teleoperation and enhance teleoperation. Several approaches have tried to design some form of mixed reality interface to enhance control for teleoperation. All of these research papers can be divided into two broad categories: approaches that attempted to create mixed reality by simply switching an egocentric view with an exocentric view, and approaches that attempted to combine and superimpose 3D reconstruction of the robot model and/or environment together to create an immersive interface.

Implementing mixed reality to an interface by switching and/or combining an egocentric view with an exocentric view is the easier option. This egocentric and exocentric view-based mixed reality can be achieved using multiple sensor inputs such as video feed, laser feed and LiDAR, amongst others. Despite having some variations amongst the techniques, the approaches described by [253,255,256] can be grouped together in this category. For all of these techniques, the teleoperator can switch between a 2D egocentric view and a 2D/3D exocentric view. This technique offers better leverage when a low bandwidth communication link is used. However, these interfaces [253,255,256] does not offer an immersive experience to the operator, although additional advisory information such as reference path, planned path, and odometry position can be integrated into the interface for both egocentric and exocentric options.

Approaches such as [199,249–252,254,256,257] fall under the category of approaches that have tried to offer a more immersive experience to the teleoperator by creating a mixed reality interface. Refs. [251,252,254,256,257] described interfaces where a 3D virtual reconstruction of the mobile robot has been added to a 2D image or video feed. As an example Fig. 12 illustrates the method described by Sugimoto et al. [257] where images captured by the camera onboard the remote robot are stored with time stamp and position information. In creating the visual feedback of the remote environment, the system looks for an appropriate image (image containing the viewpoint of the previous stage) using an evaluation function that provides information on robot position, camera position, and field of view. Once the image is selected, a 3D model of the UGV is constructed on the scene providing the operator with an impression of an exocentric view of the environment from behind the vehicle. Refs. [199,254] described interfaces that create 3D virtual model of the remote environment and a 2D video feed is then added to that 3D reconstruction.

Recent improvements to the mixed reality based robotic teleoperation user interface options include the commercially available HoloLens wearable AR glasses or the DrEAM paradigm. Use of a HoloLens for creating a mixed reality interface has been discussed in [250]. The use of the HoloLens can enable map, path, control commands and even a 3D virtual model of the mobile robot to be visualised. Drone Exocentric Advanced Metaphor (DrEAM) was named and implemented by Wojtkowski et al. [249]. DrEAM implements a world in miniature (WIM) modelling in a CAVE-like environment. In this virtual world, the operator sees a 3D re-constructed environment of the real mobile robot operating environment and can even touch the virtual robot (VUAV) and teleoperate it using basic commands via a joystick.

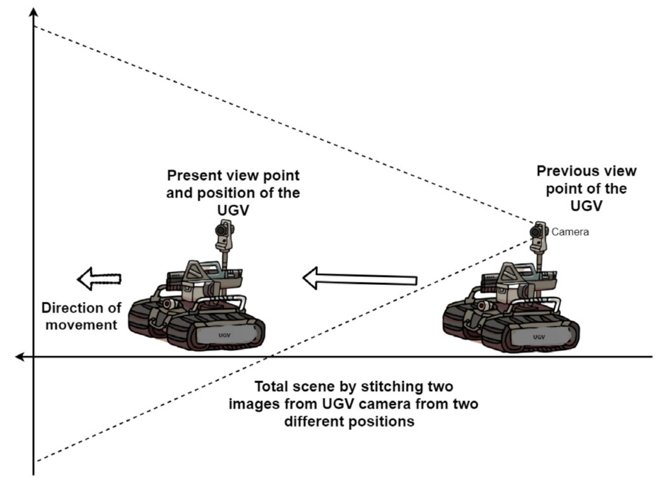

Fig. 12. The mixed reality described in [257], where a 3D model of a UGV is constructed on a previously stored scene that offers an exocentric view for the present location of the UGV.

5.3. Control system improvement

Improving the control system to make teleoperation easier is a longstanding and ongoing research priority. A large number of research papers aimed to make the control easier and we have divided their approaches into three broad categories: approaches that tried to improve system control architecture, approaches that attempt to reduce control burden by increasing local autonomy, and those that attempt to do so by implementing automatic tracking. All of these categories are discussed in this section.

5.3.1. System control improvement

Control theory and control system architecture improvement can positively affect the controllability of the mobile robot during teleoperation. All of the control system improvement techniques are equally effective regardless of the type of mobile robotic vehicle. Earlier approaches to addressing control loop delay have included [266–273]. These approaches tried to enhance controllability by applying compensation and gain adaptation algorithms to address the delay induced by the communication network and assessed their impact on teleoperation performance. Instead of applying control gain in real-time, Sheik-Nainar et al. [271] described a model where the system stored the control gain in the look-up table of the controller to avoid any deviation by the robot from its track. The system thus adapted the controller gain considering the amount of delay and the operating environment. This technique was applied to the system control method described in Tipsuwan and Chow [270]. Along with compensation and gain adaptation, [272] combines the remote operator's velocity command, sensor feedback, and the present state of the robotic platform with the time delay to set a velocity reference and modify the signal from the operator. This is a combination of delay-compensation added to both sides (operator and robot). For generating velocity reference points, the use of the Proportional Integral Derivative (PID) controller has also been recorded in [273].

A common characteristic of control improvement-based techniques is that they all assume the real-world in standard and perfect conditions. Instead of experimenting with real-world long-distance teleoperation situations, models were tested using simulation. Approaches by Slawinski et al. [272] and Dalvand and Nahavandi [273] are particularly useful for shorter manipulation segments. Moreover, a low-level interface is required to make

Table 4
Summary of control system improvement techniques.

Author (Year) [Ref.]	Technique	Medium	Robot type
System control improvement			
Dalvand and Nahavandi (2014) [273]	Control algorithm with PID controller	Internet	Manipulator
Slawinski et al. (2007) [272]	Control algorithm considering sensor feedback, operator input and robot state	Internet	UGV
Sheik-Nainar et al. (2005, 2004) [270,271]	Gain adaptation algorithm to offset delay	Internet	Remote presence system
Luke and Ray (1990) [266]; Nilsson et al. (1998) [267]	Algorithms for compensating communication delays	–	–
Automatic tracking			
Grijalva and Aguilar (2019) [136]	Colour detection based landmark tracking to avoid collision	WiFi	UAV
Cantelli et al. (2017, 2013) [155,156]	UAV feed that tracks UGV using vision based algorithm	Satellite	UGV–UAV
Klodt et al. (2015) [284]	UAV tracks UGV using vision based visibility radius tracking algorithm	–	UGV–UAV
Saakes et al. (2013) [224]	Coupled flying camera using spherical coordination technique	ZigBee	UGV–UAV
Ha and Lee (2013) [152]	UAV tracks a UGV using vision based racking algorithm	–	UGV–UAV
Local autonomy			
Sivčev et al. (2018) [132]	Collision avoidance based on the motion of the ROV and position of the destination	Umbilical cable	ROV
Ali et al. (2018) [285]; Al-Aubidy et al. (2013) [133]	Obstacle avoidance	DTMF and Internet	Mobile robot
González-Jiménez et al. (2012) [134]	Obstacle avoidance, auto docking	Internet	Giraffe remote presence system
Takayama et al. (2011) [135]	Obstacle checking and collusion avoidance	Internet	Remote presence system
Larsson et al. (2010) [137]	Edge following turning and straight movement	WLAN	LHD vehicle

these approaches effective. Therefore, use of these methods is less suitable for long-distance teleoperation of mobile robots in challenging environments.

In modern teleoperation control techniques, intelligent control methods and machine learning methods are well integrated. Neural networks (NN) have been used to deal with the system uncertainties, time delays, and external disturbances [274,275]. Sun et al. [276] and Yang et al. [277] described wave variables and NN based methods that help to estimate the system dynamics' uncertainties. Fuzzy logic-based control mechanisms have also been implemented to deal with time-varying delay and system uncertainties by Li et al. [278], Li et al. [279], and Sun et al. [280]. Impedance control methods have also been considered in several approaches such as [281–283]. However, all of these methods rely on specific models. Moreover, they are either validated using simulations or robotic manipulator systems. Therefore, these methods have not been included in Table 4.

5.3.2. Implementing automatic tracking

Due to advancements in computer vision research, automatic object tracking is gaining popularity for various applications. An overwhelming majority of the teleoperation approaches that implemented the automatic tracking technology are in multi-robot systems where a UAV assists a UGV to achieve a higher level task by providing the operator with better situational awareness. Controlling multiple robots can be extremely difficult for a single operator. Therefore, ensuring the control of the follower by automatic tracking of the leader reduces the workload and enhances teleoperation. We have included discussion of these approaches under the control system improvements, as the automatic tracking techniques improve the control system of the teleoperation loop by increasing local autonomy.

Automatic tracking has been investigated by [136,152,155,156,224,284]. For [152,284], the UAVs follow the UGVs though vision-based tracking techniques such as spherical coordinates and orientation tracking [224], marker tracking [155], trajectory tracking [284], and vision-based velocity tracking [152]. Fig. 8 displays a schematic diagram of UAV–UGV coordination using spherical coordinate and orientation tracking as applied in [224]. For [156], the UGV–UAV coordination is opposite and the UGV tracks and follows the UAV by an image-based object tracking algorithm applied on a feed from an upward-looking camera and WebGIS platform for pre-path planning. In recent work, Grijalva and Aguilar [136] proposed landmark detection based obstacle avoidance for UAVs where the UAV detects and follow a pre-prepared landmark to avoid any collision.

Although only demonstrated for UGV–UAV coordination, vision-based tracking systems can be implemented for all mobile vehicle types. However, vision-based tracking can fail for swarms and environments that create occlusion issues. Some of the above techniques also require the provision of the landmark to the system. All of the above mentioned approaches tried to use conventional vision based tracking algorithms to establish coordination in a multi robotic vehicle situation. Modern deep-learning based object detection and tracking techniques can be used to provide more automation capability to the robotic vehicles and reduce workload for the operator.

5.3.3. Increasing local autonomy

Providing teleoperated mobile robots with more local autonomy is an effective way to reduce the burden on teleoperators. As fully autonomous robots capable of performing critical tasks without supervision is still the subject of long term future research, an intermediary step involving an increased amount of onboard sensors and decision making autonomy for obstacle avoidance, auto-docking, following real-time maps, and navigating safely without human intervention, can feature as effective ways to enhance teleoperation performance.

The type of local autonomy so far added to teleoperated mobile robotic vehicles include following of tunnel edges and positioning inside mining tunnels [137], obstacle avoidance [134,135], autodocking [134], obstacle detection [133,285], and collision avoidance [132]. All of these local autonomy capabilities can be incorporated with all types of mobile robotic vehicles.

Autonomous navigation and automatic path planning are large and active research domains for autonomous cars, and autonomous robotic vehicles [286,287]. These navigation and path planning systems can achieve high precision using laser or LiDAR scanners combined with global positioning systems (GPS) [288]. RGB camera feeds and deep learning methods have also been used in recent work for automatic navigation [289]. However, this review primarily focusses on the local autonomy of teleoperated robotic vehicles. The main finding is that, thus far, local autonomy for teleoperated robotic vehicles is limited to basic obstacle detection and avoidance, auto docking, and following trails. Although these help the teleoperator ensure relatively safer teleoperation, they are still inadequate to allow efficient teleoperation of robotic vehicles in challenging environments with reasonable ground speed over high latency connections.

5.4. Latency compensation

Increased perceptional awareness of the environment enhances control over teleoperated mobile vehicles. However, communication delays between the teleoperator and the robotic platform are inevitable and can significantly degrade performance. In challenging environments, longer and time-varying delays can even make effective teleoperation impossible [290]. One prospective way to reduce the impact of teleoperation delay is by predicting the evolution of the state variable for the period of the delay [291,292]. Based on the surveyed published works, we have subdivided the predictive feedback based mobile robot teleoperation systems into 2D and 3D predictive interfaces which are discussed in this section.

5.4.1. 2D predictive interface

Delays in the control loop motivated the development of predictive displays from as early as the 1990s. The predictive interface design research gained momentum to ease space-based high latency manipulator arm teleoperation. [293–295], and [296] tried to implement the concept of a predictive display that allows the operator to view the response of the system before it actually happens and hence avoid possible collisions. As we intend to avoid discussing telemanipulators, detailed discussions are avoided.

The use of predictive displays along with system control improvement was reported for mobile robot teleoperation by Witus et al. [106]. The authors attempted to enhance teleoperation by the state prediction of a UGV through iconography in the user interface intended for AR and VR display. A theoretical improvement of such a mobile robot state prediction was proposed by Wang et al. [297]. To resolve the nonlinearities for delayed teleoperation, [297] proposed to transform the Laplacian matrix into the real Jordan form. Their approach considered system state integral terms by tentatively applying the Krasovskii functional method. Some other predictive frameworks that do not include predictive displays as an operator aid, and only incorporate algorithm based predictions, includes the work by Zheng et al. [298] who describes a model-free predictor frame work for UGVs and Zhang and Li [299] who tried to design a predictor model based on the Clohessy–Wiltshire relative dynamic equation. However, iconography or non-visual state prediction for video feed based teleoperation of mobile robots operated at reasonable ground speed has not been shown to be an effective technique.

Future pose and location estimation in a 2D user interface is an enhancement to the techniques described in the previous paragraph. For a set of non-holonomic mobile robots, Ha et al. [151] designed a 2D predictive display that shows the current and the future poses of all of the mobile robots in the group. The technique introduced by [151] can be described as a propagation stage prediction for a leader followers multi-robot system that has a prediction horizon of up to two metres. This technique will, however, fail for single mobile robot systems, swarms having complex formation or leader followers systems with reasonable ground speed.

2D Image transformation may contribute significantly to the predictive display-based interface design. A few approaches have indicated its prospective usability in teleoperation interface design. Matheson et al. [300] experimented with simple image transformations such as cropping and zooming applied to teleoperation of a single direction forward-moving vehicle and tried to provide a future prediction to the trajectory. Dybvik et al. [301] applied positional and scale transformation into video feeds and tried to predict and indicate the future trajectory of an ROV. However, both of these applications were on slow-moving mobile robots in a controlled environment and were not suitable for UGVs. Combining multiple image and video transformation techniques and accounting for the mobile robot's speed, change of direction and trajectory may help to design a 2D predictive interface that can enhance teleoperation for robots with reasonable ground speed and in real-world challenging environment (see Table 5).

5.4.2. 3D predictive feedback

As VR, AR, and MR can increase perceptional awareness of the operator, some approaches assume a 3D predictive display might be a better solution than a 2D predictive display, as they offer additional environmental perception.

A small number of research articles have described 3D predictive interfaces for latency compensation including [303,304], and [305]. Out of these, Deng and Jagersand [305] designed a predictive display specifically for telemanipulation. All of these approaches have a common technique to achieve 3D predicted feedback. They all created some form of parallel virtual robot environment and tried to exhibit the immediate reaction of the mobile robot in the virtual interface bypassing the control signal travelling through the communication loop. These approaches represent calibrated virtual robots on the user interface along with the regular feed. This calibrated robot shows the consequences of the operator commands in real-time. Therefore, before getting the actual visual feedback from the environment, operators can generate action commands. Fig. 13 shows the schematic diagram of the system as developed by Xiong et al. [303]. Ricks et al. [304] generated the parallel virtual environment from sonar sensor data and named the visual display "3D ecological display". The 3D ecological display provides a 3D representation of the immediate last command calculating the time since the command was sent instead of the time it takes to process on the remote platform.

All of these predictive approaches have tried to limit the impact of latency through the representation of the visual impact of commands. These above approaches can be categorised as first-order prediction techniques, which is of little value for long-distance teleoperation in higher latency conditions. Moreover, these prediction techniques do not include factors related to the uncertainty of future events. Modern techniques of 3D reconstruction of point-cloud [306] or point-voxel [307] can be used for virtual environment generation. Deep generative neural networks can potentially be trained on these point-clouds/voxel data to generate a predictive future.

5.5. Multimodal teleoperation system

Besides all of the visual and non-visual perception enhancement approaches, situational awareness enhancement using multi-sensory feedback or multimodal interfaces is a new stream of research for robot teleoperation enhancement. A promising direction in this new research domain is to combine visual,

Table 5
Summary of latency compensation techniques.

Author (Year) [Ref.]	Technique	Medium	Robot type
2D predictive feedback			
Dybvik et al. (2020) [301]	Positional and scale transformation to the video display	Wired connection	Wheeled ROV
Wilde et al. (2020) [302]	Predictive flight path using velocity telemetry, camera feed and control inceptor deflection	WiFi	UAV
Ha et al. (2018) [151]	Future state and collision prediction for a multi mobile robot leader–follower system	–	Wheeled ROV
Wang et al. (2016) [297]	Truncated prediction of states for nonlinear multi-agent teleoperation	Any medium	–
Matheson et al. (2013) [300] Witus et al. (2011) [106]	Projected field of view by cropping and zooming	Wireless	Space Rover
3D predictive feedback			
Xiong et al. (2006) [303]	Predictive display that shows command consequences in real-time	–	6-DOF manipulator arm
Ricks et al. (2004) [304]	Robot state prediction from velocity and timestamp information	–	Simulation
Deng and Jagersand (2003) [305]	Parallel virtual machine (PVM) to replicate the current states of robot in a delayed teleoperation	Ethernet	Pan-Tilt

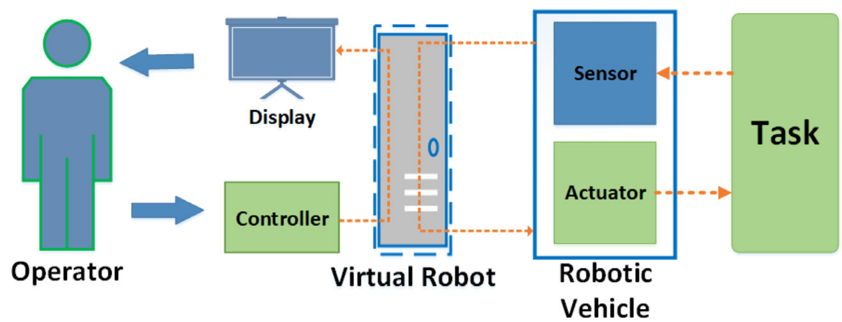

Fig. 13. Schematic diagram of teleoperation using predictive display described by Xiong et al. [303].

auditory, and haptic sensor feedback and provide the teleoperator an immersive solution. All of the haptic feedback and local autonomy based enhancement techniques discussed earlier used multi sensory feedback or used multimodal enhancement techniques. These are therefore not discussed again to avoid repetition. The only multimodal mobile robot teleoperation system that was not introduced previously in this paper is by [308]. Triantafyllidis et al. [308] described a system where the authors used a VR head-mounted stereoscopic visual interface, stereo headset for auditory feedback, and a haptic capable glove for providing vibrotactile feedback. Their study shows that this combination performs better than each of the feedback types individually. Although it may be a general perception that adding more modalities increases the teleoperator performance [309], at a certain point more modalities can make the operator overwhelmed and ultimately decrease the performance. Triantafyllidis et al. [308] also showed their auditory system has little to no impact on teleoperation performance.

5.6. Summary

Based on our review of the literature, teleoperation enhancement has recently been focused across five broad categories of research: operator perception enhancement, user interface improvement, control system improvement, latency compensation, and facilitating multimodality. Research suggests that egocentric and exocentric view exchange, automation of viewpoint adjustment and tracking, 2D and 3D map generation and automated path planning can enhance teleoperators' visual perception of the remote environment. Adding tactile feedback offers additional situational awareness and potentially enhances the teleoperation, however, latency over a specific threshold in the data transmission can destroy the positive gain achieved through perception enhancement.

Enhancing situational awareness by improving the teleoperation interface is a major domain in the teleoperation enhancement research field. Research suggests interfaces that incorporate stereoscopic vision or provide visual representations of environmental sound and force can contribute to better situational awareness. Additionally, achieving multimodality through multisensory feedback is a new and promising research direction for interface design. However, all of these techniques, tend to create an increased amount of information that can be irrelevant, can increase cognitive workload, and requires higher bandwidth.

Research suggests that physical and psychological immersion into a virtual remote environment achieved through interfaces designed with the help of VR or AR HMDs, haptic workstations, and image-based 2D and 3D virtual worlds offers the operator additional situational awareness and helps enhance operator experience. For a large number of use-cases, these immersive techniques are robot type and remote environment-specific, however, and therefore non transferable. VR, AR, and MR based interfaces also require higher computation capability and increase the visual delay to the control loop.

Another avenue of research that aims to enhance teleoperation is through control system improvement. In addition to control loop delay compensation and gain adaptation, a large amount of control system research is also dedicated to automatic tracking, obstacle avoidance, auto docking, path planning, map following, and automatic navigation to help the robot increase local autonomy and change the dimension of responsibility sharing in a teleoperation task. However, it is common in control system research for the assumption to be that the remote environment is in a standard and ideal condition, ignoring the system's uncertainties and external disturbances. Moreover, the majority of the research works surveyed were evaluated in a simulated world, and not tested in real-world scenarios. Heavy computation is also required on the mobile robot end.

According to our literature survey, the majority of the teleoperation research projects are focused on enhancements to situational awareness. A major drawback to all of these studies is that they themselves induce latency to the control loop, or are incapable of addressing communication link related challenges. To attempt to overcome these limitations, there are some research works that introduce predictive interfaces for teleoperators. The majority of these are iconography, non-visual state prediction, or immediate virtual robot reaction prediction after a control command. Therefore, there are great opportunities for research in improved predictive teleoperation interfaces.

6. Evaluation criteria of teleoperation performance

Based on the previous discussions in this paper, it is apparent that the teleoperation research domain is a large and complex research area. Although we have attempted to classify types of mobile robots and their enhancement technologies into broad categories, every approach mentioned and discussed in this paper designed unique experimentation conditions and individual evaluation and validation parameters to test their novel approaches. Due to these differences of the robot types, their functionality, type of enhancement, and the differences in evaluation parameters we have not attempted a comparative analysis among approaches. We do not believe that comparing these techniques with each other through some defined set of parameters will offer a valid judgement of the techniques discussed. However, in this section we have introduced a categorisation of the range of evaluation techniques that have been applied to these teleoperation systems along with references where the details of these criteria can be found.

6.1. Human operator survey

To evaluate teleoperation approaches and enhancement techniques, an overwhelming majority of the papers relied on some form of human operator based survey. In these surveys, the operators tested the teleoperation systems by completing tasks such as simple driving of a robotic vehicle through a predefined track [113,135,137,151,180,190,199,204,209,210,218,227,237,241,249,254,255,257,271,272,300,304], identifying objects or targets in the environment [156,203,217,224,226,248], picking and placing [107,211,246], throwing objects to targets [301], or simply operating the robot to park it closely to a obstacle [233,245]. During these human teleoperation sessions, the quantitative evaluation criteria used include a comparison of completion time, the number of collisions occurred, comparison of robot position and movement against reference positions, the velocity of the mobile robot, distance travelled in a specific time frame, the number of commands to execute a task, trajectory comparison with the track, comparison of target distance and actual distance, the number of objects picked and placed, and the number of hits and misses for a task amongst others.

For a large number of approaches, the authors preferred subjective or qualitative feedback from the teleoperators about the quality of the system, quality of the visual interface, usability, comfort, richness of the situational awareness, control, satisfaction, level of difficulty and so on [40,132,190,211,227,233,254,257]. Reducing operator stress and workload are important to enhance teleoperation outcomes. A few approaches [135,201,249,299,300] used the NASA-Task Load Index (NASA-TLX) [310] to estimate the workloads during the experimental teleoperation sessions. NASA-TLX measures the mental, physical and temporal demand, frustrations, and performance effort of an operator.

6.2. Image analysis

Teleoperation sessions that use visual feedback as a principal mode of situational awareness, and aims to enhance the situational awareness by improving the visual feed can be evaluated by image or video analysis. Although most of these interfaces and visual feed enhancement based teleoperation enhancement techniques relied on the teleoperators subjective feedback about the quality of the interface and visual feed, some approaches such as [136,200,207,208,238,304] used image-based analysis to evaluate the enhancement. The image analysis includes computation of object displacement [200,238], or simply pixel-based comparison using peak signal to noise ratio (PSNR), structural similarity index (SSIM) and/or root mean square error (RMSE) [136,207].

6.3. Trajectory comparison

Calculating the trajectories of teleoperated robots affected by latency, intermittent communication, degradation of situational awareness, or control issue and comparing with ground truths have been used to evaluate teleoperation enhancement by several approaches [151,152,155,173,224,272,284,302,305]. Trajectory comparison graphs are a great way to display the dissimilarity between different enhancement techniques and their impact on following a route by a teleoperated mobile vehicle. Most of these trajectory comparison based evaluations were applied to teleoperated aerial vehicles through position, altitude, pitch and angle comparisons.

6.4. Statistical analysis

Statistical analysis such as ANOVA, Shapiro–Wilk test, and Wilcoxon test on vibration patterns, velocity, movements, gain adaptations, workloads and subjective operator feedback have been used in [184,187,201,301]. Statistical analysis using these tests are effective methods for checking the integrity of the test data and their normality. ANOVA and normality graphs have been used to see the data distribution (operator survey) and Shapiro–Wilk and Wilcoxon tests have been used to test the underlying hypothesis of whether an enhancement technique was useful and preferred by the operators. Statistical data visualisation techniques such as normal graphs, box plots, score plots, and bar graphs have also proven helpful to evaluate teleoperation performance [184,187,201,301].

Due to the complexity, differences between mobile robots, control techniques, types of interfaces, feedback for creating situational awareness, and the variety of intended purposes for the mobile robot, it is very difficult to formulate a generalised and uniform evaluation technique for mobile robot teleoperation. Similar to the NASA-TLX cognitive workload calculation metric, future research can be directed to develop a more generalised tool for evaluating the overall performance of mobile robot teleoperation.

7. Research challenges

The previous sections of this paper categorised and briefly described the state-of-the-art in mobile robot teleoperation methods and their enhancement techniques. However, a well-developed, effective robotic teleoperation method and interface still requires significant research work that will address the situational awareness, control, and teleoperation delay aspects. There are a number of significant challenges that need to be addressed to develop techniques that enhance control on mobile robots based on both visual and non-visual feedback to the operator. The principal challenges can be described as follows.

7.1. Challenges related to the user interface

One of the challenges for developing a visual feedback-based assistive user interface is to set up the optimal required parameters for a scene such as field of view, required number of feeds, acceptable resolution for safe vehicle operation, etc. The keyhole or the soda straw effect is one of the major challenges for teleoperation when the control is executed based on a video feed [311]. This negatively affects environmental perception by affecting target detection capability and locational awareness [312]. Other challenges related to the limited field of view include difficulty in judging the speed of the vehicle, time to collusion, and location, or the start of a curve, amongst others [313]. For teleoperation, if an immersive display (conventionally used for ground robotic vehicles) is used instead of an exocentric frame of reference (FOR) (generally used for UGVs), teleoperators show signs of cognitive tunnelling [314]. Finding the best practices and incorporating them into the predictive system can reduce negative bias and increase effectiveness.

Determining the optimal trade-off between tasks, mobile robot types, teleoperation methods, robot speed, teleoperators performance, the combination of sensors, and modes is a challenge for teleoperation research. Further, For visual feedback based teleoperation interfaces the need to trade-off between frame rates, pixels per frame, bits per frame (levels of brightness or grey-scale) is a challenge [315]. Studies performed by Chen et al. [316], Massimino and Sheridan [317], and Van Erp and Padmos [313] suggest speed and motion perceptions significantly degrade below 10 Hz. Studies by Thropp and Chen [318] and Watson et al. [319] suggest anything less than 17.5 Hz will affect teleoperator performance. Further, different user interface types (stereoscopic vs monoscopic) will require different frame rates for effective teleoperation [320]. Trading off these parameters among each other is a significant challenge to optimise the control over teleoperation [321].

For enhancing teleoperator performance, haptic feedback methods are popular techniques where the operators are considered as a passive agent. However, there are research results that show that the enhancement by the vibro-tactile or haptic systems are highly influenced by the status of the operator [33] and require almost constant input. Moreover, the existing haptic feedback systems do not consider the uncertainty and the mechanical impedance of the operator. Further, the current techniques lack real-time monitoring of the teleoperators' body status and modification of the control decisions accordingly. Other non-visual enhancement techniques include local autonomy. However, local autonomy is currently limited to obstacle avoidance, auto docking, or edge following only.

Multimodal or multi-sensor teleoperation systems offer additional feedback from the robot working environment. However, the current systems and user interfaces do not provide an amalgamated and easy to follow outlook. Therefore, teleoperators often get overburdened by multiple sources of information.

Although there are some similar aspects of human–robot interface (HRI) and computer-supported workgroups (CSCW) [322], human–robot interaction is different than that of human–computer interaction [52]. Therefore, the transition of present human–computer centric interface ideas to proper user-friendly robot teleoperation interfaces is a significant challenge. Managing the level of data details in an HRI to emphasise the key aspect of the remote environment and the robot state without increasing the cognitive load on the operator is a key challenge of robot teleportation user interface design [48]. Adding social aspects to a teleoperation interface can help reduce operator stress and workload. Implementing the concept of social interface is, thus, also a teleoperated robot interface design challenge [51].

7.2. Challenges related to the communication link

7.2.1. Limited bandwidth:

Teleoperation methods and enhancement techniques that use video feed, visual tracking, image-based rendering, or incorporating AR, VR, or MR require high-quality video data transmission and are significantly constrained by the high-bandwidth requirement. Low-bandwidth results in impoverished video feed representation, which often causes poor spatial awareness and could eliminate cues that are vital for the formation of teleoperators' imaginary model of the environment [321,323]. However, in challenging environments, bandwidth availability could be highly limited. Distance, electronic jamming, or obstacles can impose challenges to maintain sufficient signal strength [324]. Finding a bliss point for the bandwidth requirement and effectively enhanced teleoperation is a challenge.

7.2.2. Latency

Latency creates significant difficulties to teleoperation tasks. Variable latency is more problematic than constant latency. The greater the standard deviation of the latency, the more it degrades teleoperators' control over a vehicle. Addressing variable latency while enhancing teleoperation through predictive virtual environment models is a significant challenge for smoother long-distance teleoperation.

Predictive feedback-based techniques attempt to offer the teleoperators a tool to cope with the communication delay for long-distance teleoperation. However, all the predictive techniques provide first-order prediction such as prediction of the state of the robot, the future direction of movements, projected field of view, or simply the replication of the remote environment in a parallel virtual machine. Moreover, these predictive techniques do not consider the stochastic nature of the future or provide long predictions for the future.

Two-dimensional or three-dimensional visual aid based teleoperation enhancement techniques such as AR, VR, MR, or map merging techniques require high computation capability and often add additional processing time to the usual communication delay.

7.3. Challenges related to control techniques

A well developed control technique need to resolve six major inherent control issues: (a) operator model estimation, (b) environment model estimation, (c) master model uncertainties, (d) slave model uncertainties, (e) communication delays, and (f) external disturbances [28]. However, addressing all of these issues while maintaining system stability is a major challenge for teleoperation control techniques. There are a large number of control theories and mechanisms that have been proposed, utilised, and described in the literature. However, there is no unique control technique available that is suitable for a large number of cases. Every methodology considers specific features and requirements. A large number of old techniques cannot be accomplished in discrete time frames; therefore, they cannot be used for modern digital systems. Moreover, these control techniques are focused on controllers and local systems and do not pay attention to communication characteristics [24].

8. Future research directions

From the discussion in the previous sections, it is evident that an enhancement to the robot teleoperation system can be achieved by improving the user interface to facilitate better situational awareness, reducing impacts of latency, and improving the control system. This section provides some possible directions for future research covering all these three broad teleoperation challenges.

8.1. User interface design

To enhance the teleoperation experience of the operators, there are opportunities for cross-domain research for human–robot interface design (HRI), computer vision (CV), and visualisation (VIS) researchers. As discussed in Section 7, a major challenge in interface design for teleoperation is the addition and amalgamation of multimodal feedback in the interface. Research can be carried out on how to synthesise complex image data from sources such as digital cameras, LiDAR, laser, and spectral imagers with other forms of data such as haptic feedback without increasing the operator cognitive workload. Determining the optimal trade-off parameters and information from a visual interface poses a significant challenge. Therefore, research can also be carried out on the use of AI to help an operator reason and pick the most related information from the user interface.

Transitioning from Human–Computer interaction centric interface design ideas to proper Human–Robot interface design is a significant challenge. Designing mixed-initiative systems [325, 326] and incorporating social interaction techniques to the user interface can improve the communication between the operator and the interface. Techniques such as facial expression recognition [327], human emotion recognition [328], posture recognition [329], skin conductivity [330], and recognition of other social communication signals [331] can be used to create a more interactive user interface and virtual co-pilot agent [51], to help reduce the operator workload in the mixed-initiative system. Achieving an immersive experience without overwhelming the operator is a great challenge. Therefore, for better immersive experiences for the operator, research can be driven towards the improvement of the VR, AR, and MR interfaces.

8.2. Latency compensation

As noted in Section 7.2.2, latency is one of the most significant challenges, especially for long-distance teleoperation. For latency compensation, a widely used technique is to predict the future states of the robot. However, the major drawback and challenge to the existing techniques (described in Sections 5.4 and 7.2.2) is that the prediction is limited to only first-order state or direction prediction. Given that, for most teleoperation models, continuous video feedback is the primary means used to determine the robot's state, future video frame prediction may eliminate or reduce the impact of the delay. If the future frames prediction and generation can be supervised and controlled in real-time using both the control inputs from the teleoperator and the video feed from the robotic vehicle, the generated future feed could potentially provide a relatively accurate prediction of the actual future view, within some forward-looking horizon. Synthetic video generation and future frames prediction research is gaining in popularity in computer vision problem domains such as driver-less car technology [332], video-based weather forecast [333], traffic monitoring [334], and many more. However, methods of teleoperation enhancement through future frames prediction have not yet been reported. Therefore, investigating emerging future frame prediction techniques and customising them for robotic vehicle teleoperation could be a promising future research direction.

To provide solid evidence towards the potential of using future frames prediction techniques to enhance robotic teleoperation, we surveyed the literature deeply. Future frame prediction is a relatively recent field of research for the computer vision research community. It has suddenly attracted a great deal of interest due to its applicability to autonomous car technology, mining, space exploration, and robotics. Fig. 14 shows a significant rise in video frame prediction research in recent years.

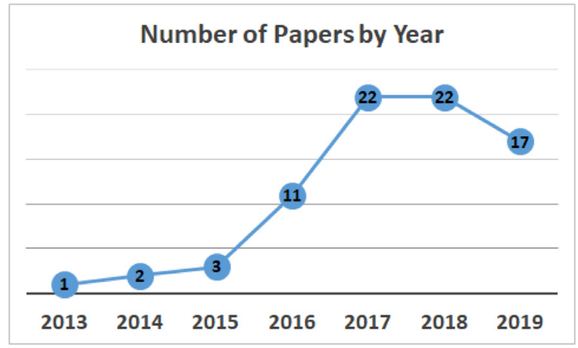

Fig. 14. Research interest into future video prediction based on an estimate of the number of yearly publications.

Although achieving realistic outcomes with video frame prediction techniques will be an extended research process, a number of different approaches and techniques, as well as combinations of multiple techniques have the potential to be used in teleoperation systems to generate future and continuous video feed from the incoming and delayed video feed from the robot camera. Some of these approaches and techniques are briefly discussed for the convenience of the teleoperation research community. Table 6 lists some of the most promising recent future prediction techniques that can be used as a base-line for creating future technologies for teleoperation enhancement.

8.2.1. Pixel synthesis

Pixel synthesis is a method that generates the next pixel for the predicted future frames. Most recent pixel synthesis based future frame prediction techniques that generate a significantly large number of future frames and have the potential to be used for continuous future prediction for teleoperation include CrevNet by Yu et al. [335], GAN-VGG by Shouno [336] and Spatial wavelet analysis module (S-WAM) by Jin et al. [337]. All of these pixel synthesis models can generate more than ten future frames for data sets that can preserve finer details and textures of the environment of ground vehicle teleoperation.

8.2.2. Pixel transformation

Pixel transformation is the technique that transforms input pixels to construct new pixels for frames to generate predicted future video. This technique is capable of dealing with pixel redundancy and similarity between consecutive frames. Convolutional long short-term memory (ConvLSTM) [333] block-based flexible spatio-temporal network (FSTN) by Lu et al. [340] is capable of predicting 36 sharp future frames by transforming 4 input frames. Vondrick and Torralba's [339] adversarial pixel transformation can generate videos of plausible features. This model can generate 12 future frames from four input frames. The latest improvement of this adversarial plausible future transformation is by Luc et al. [338]. They improved clark's [351] DVD-GAN-FP model and proposed a TrIVD-DVD-GAN-FP model that can predict the future by transforming pixels for complex real-world scenes. Therefore, these transformation models have high potential to be used for real-world teleoperation enhancement by future video prediction and generation.

8.2.3. Motion and content separation

Motion and content separation methods are inspired by action recognition two-stream architectures [352]. In this technique, motion of an agent in a frame is separated from the background, and the future flow of that agent is predicted. A pixel synthesis or pixel transformation is performed to render new frames based

Table 6
Future video prediction techniques that have the potential to be utilised to enhance teleoperation (**RGB:** Red Green Blue; **A:** Action; **S:** State; **SS:** Semantic Segmentation; **D:** Depth; **M:** Motion; **Po:** Pose; **MSE:** Mean Squared Error; **AL:** Adversarial Loss; **PL:** Perceptual Loss; **GDL:** Gradient Difference Loss; **CE:** Cross Entropy; **l1:** Least Absolute Deviation (LAD); **l2:** Least Square Errors (LES); **KL:** Kullback–Leibler Divergence).

Author (Year) [Ref.]	Model	Input–Output	Loss function	Number of predicted frames
Pixel synthesis				
Yu et al. (2019) [335]	CrevNet (3d-cED)	RGB–RGB	MSE	10+
Shouno et al. (2020) [336]	GAN-VGG	RGB–RGB	AL, PL, Lp	10+
Jin et al. (2020) [337]	S-WAM (cED-GAN)	RGB–RGB	AL, GDL	10+
Pixel transformation				
Luc et al. (2020) [338]	TrIVD-DVD-GAN-FP	RGB–RGB	L-hing	10+
Vondrick and Torralba (2017) [339]	cGAN	RGB–RGB	CE, AL	10+
Lu et al. (2017) [340]	LSTM-cED	RGB–RGB	PL	10+
Motion and content separation				
Denton et al. (2017) [341]	LSTM-ED	RGB–RGB	l2, CE, AL	100+
Villegas et al. (2017) [342]	LSTM-cED	RGB–RGB	AL, GDL, Lp	10+
Conditioning extra variables				
Finn et al. (2016) [343]	ST-CLSTMs	RGB, A, S-RGB	l2	10+
Oh et al. (2015) [344]	rED	RGB, A-RGB	l2	100+
Probabilistic models				
Hu et al. (2020) [345]	cED	RGB-SS, D, M	CE, Lp, Lc	10+
Castrejon et al. (2019) [346]	vRNN VAE	RGB–RGB	KL	10+
Denton and Fergus (2018) [347]	LSTM-cED	RGB–RGB	KL,l2	100+
Babaeizadeh et al. (2017) [348]	SV2P (CDNA)	RGB–RGB	KL, Lp	10+
Extracting high level features				
Wichers et al. (2018) [349]	LSTM-ED	RGB–RGB	AL, l2	100+
Villegas (2017) [350]	LSTM-cED	RGB, Po-RGB, Po	AL, PL, l2	100+

on the predicted motion flow. The state-of-the-art for motion and content separation technique for future video generation are described by Denton et al. [341] and Villegas et al. [342]. Denton et al. [341] used a standard LSTM encoder–decoder to generate 100 future frames and Villegas et al. [342] used a Convolutional LSTM to generate 30 future frames. These motion and content separation techniques could be a promising option for prediction of future states of robotic manipulators through a live video feed.

8.2.4. Conditioning extra variables

Predicting the future based on only the motion of an object can provide an erroneous outcome as the future is highly uncertain. Therefore, the motion and content separation technique can be reinforced by adding extra variables such as external force, robotic vehicle speed, or robot state, amongst others. Oh et al. [344] used control inputs as additional control variables for long future prediction (more than 100 frames). For natural videos, in addition to the control input, the robot state and manipulator object interaction were accounted for as extra variables by Finn et al. [343]. Finn et al. [343]'s model was able to predict 17 frames into the future. Similar to the motion and content separation approaches, these methods can be integrated for stationary robotic manipulator teleoperation enhancement. This field of research can be of significant potential future interest for the robotic teleoperation domain.

8.2.5. Probabilistic models

The future is highly probabilistic. Although extra conditioning variables would significantly narrow down the probability space, there could still be multiple future scenes for the same input sequence. The first approach of providing probabilistic multi-frame prediction was described by Babaei-zadeh et al. [348] named stochastic variational video prediction (SV2P). Later promising probabilistic models include LSTM-cED based stochastic video generation learned prior (SVG-LP) by Denton at al. [341] that generates 100 future frames for robot manipulator motion video, recurrent neural network(VRNN) based variational autoencoder (VAE) generating for urban driving video feed by Castrejon et al. [346], and geometry and motion understanding encoder–decoder network model by Hu et al. [345]. These probabilistic models have the capability to add new dynamics to robotic teleoperation and help the operator make a more realistic and less erroneous future control decision. Therefore, future research may include probabilistic future video prediction for long-distance robotic teleoperation.

8.2.6. Extracting high level features

Instance and semantic segmentation are prevalent for computer vision and future video prediction research. However, other low dimensional and high-level features such as object pose or keypoint detection may represent a promising future research direction for video-based predictive teleoperation. Wichers et al. [349] and Villegas et al. [350] described long term future video generation (126 frames) using human pose estimation and foreground prediction. Estimating the pose of agents present in a scene and generating future frames based on the prediction can help reduce collision and lead to better control decisions by the teleoperator. Therefore, a user interface design incorporating high-level feature extraction and future frames generation has high future research potential.

8.3. Overcoming bandwidth constraints

A large number of state-of-the-art teleoperation enhancement techniques such as multimodality, image-based rendering, tracking, AR, VR, MR, and others are affected by limited bandwidth, jitter, and intermittent communication links. Future teleoperation research can fuse image super-resolution [353,354] and video frame interpolation [355] to the interface end, and image compression [356] and video compression [357] techniques to the robot end to reduce the impact of bandwidth related issues. Moreover, deep neural network based new frame generation techniques can be utilised to generate a video feed that will mimic the ground truth to help overcome latency.

9. Conclusion

The prime intention of this paper is to aggregate, condense and present the current state-of-the-art methods and techniques for mobile robot teleoperation, and teleoperation enhancement, determine the research gaps and challenges and finally, offer possible future research directions. Although the methods and techniques described in the paper can be related and implemented for all teleoperation scenarios, for brevity, the paper focuses only on teleoperated mobile robots. This paper listed and categorised around 40 methods of robotic vehicle teleoperations and more than 70 different techniques to enhance these existing methods. In recent years, AI-based user interface design, deep neural networks, image-based object detection, human emotion and gesture recognition, future video frames prediction, image and video generation, and adaptive control techniques have emerged as promising research domains. This paper argues that the cross-domain research and transfer of these state-of-the-art techniques to teleoperation research can significantly enhance the operator perception of the environment, control of the robot, and reduce operator workload, error and impacts of latency. To offer an example, this paper describes a large number of future video frame prediction techniques and argues for their potential to address the challenge of communication channel latency if the prediction can be supervised and controlled by both the real-time video feed and the control inputs. This paper also presented a comparative summary of the presented techniques and methods in the form of tables. This paper concludes that teleoperation enhancement is a challenging task with significant research gaps that will require significant multi-disciplinary research efforts to address.

CRediT authorship contribution statement

MD Moniruzzaman: Conceptualisation, Literature review, Manuscript preparation. **Alexander Rassau:** Conceptualisation, Correction, Supervision. **Douglas Chai:** Conceptualisation, Correction, Supervision. **Syed Mohammed Shamsul Islam:** Conceptualisation, Correction, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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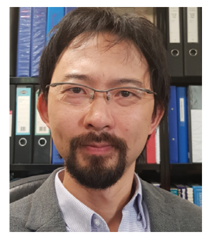

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