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A Review on Teleoperation of Mobile Ground Robots: Architecture and Situation Awareness

Samwel Opiyo, Jun Zhou*, Emmy Mwangi, Wang Kai, and Idris Sunusi

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Abstract: Currently, the application of mobile ground robots spans a range of fields from surveillance, search and rescue, exploration, agriculture, military among others. In unstructured and dangerous environments such as disaster scene, military fields or chemical spray in agricultural farms, the experience and intelligence of the operator are necessary for making complex decisions beyond the autonomy of the robot. In such cases, teleoperation allow the operator to guide the robot in achieving complex task from a safe location. The effectiveness with which the operator controls the robot depends on, among others, operator's awareness of the robot's environment, the quality of communication link, the robustness of robot's control system and experience of the human operator. Ground mobile robots form the basis of this work since they are applicable in many fields and mostly operate in dynamic environments that require additional guidance from a human operator. This study reviews research work on mobile robot teleoperation systems, and puts more emphasis on the architecture, communication link and situation awareness creation. Moreover, future trend in mobile robot teleoperation is also put forward in this review to give ground for new research work in this field. Based on the sited literature, it is noted that making the operator feel present in the robot's environment through sufficient visual and force feedback as well as use of good quality network, significantly improve the navigation efficiency and task achievement of mobile ground robots.

Keywords: Human-robot interaction, mobile ground robot, semi-autonomous robot, situation awareness, teleoperation, teleoperation architecture.

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1. INTRODUCTION

Teleoperation system is a system that allows human operator to interact with a remote environment [1, 2]. The term teleoperation is derived from two Greek words *tele* and *operation* meaning distance and to carry out a task respectively. The distance may be physical, for instance, a human operator controlling a robot at a remote location, or a change in scale such as a surgeon employing teleoperation to carry out surgery at the micro-scale level. Boboc *et al*. [3] define teleoperation as the operation of a robot or a system from a distant location when the operating environment is dangerous or impractical. This method differs from passive monitoring since it allows the operator to actually interact with the robot's environment [4] through the commands and feedback from the remote site. This mode is of great importance since humans can recognize and adapt to the environmental changes hence can control the robot better in complex situations. Fig. 1 shows a flow chart describing teleoperation process. In the figure, the operator in a local environment issues commands that are processed for transmission over a communication link to the robot in the remote site. Once the commands reach the remote site, they are decoded to a state 'well understood' by the robot controller hence controlling the actuators as desired by the operator. The existing sensor system onboard the robot gives a number of feedback to the operator. Basically, the most important feedback is the visual feedback that enables the operator easily comprehend the robot's environment. Other feedback may include, haptic or range feedback. It must be noted that the sensor signals may be drastically affected by noise hence making it difficult for the operator to smoothly control the robot. This calls for a raft of measures to aid the operator including sensor fusion, use of multiple views (this may increase the cognitive work load at the same time), as well as having a virtual model of the robot.

Despite the high human intelligence and experience (in some cases), the operator cannot entirely oversee the expected tasks of a remote robot. This means that the mo-

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Samwel Opiyo is with the College of Engineering, Nanjing Agricultural University, Nanjing 210031, China, and the School of Science, Catholic University of Eastern Africa, 62157-00200, Nairobi, Kenya (e-mail: samopiyo11@gmail.com). Jun Zhou, Emmy Mwangi, Wang Kai, and Idris Sunusi are with the College of Engineering, Nanjing Agricultural University, Nanjing 210031, China (e-mails: zhoujun@njau.edu.cn, mwangi.emmy1@yahoo.com, wk65010@163.com, idrisyaro500@yahoo.com).
* Corresponding author.

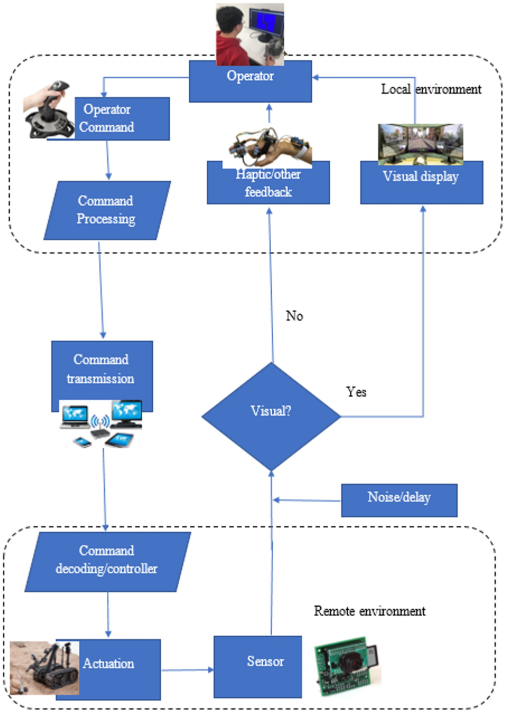

Fig. 1. Flow chart describing teleoperation process.

bile robot must at least have some level of autonomy to achieve tasks such as path planning, data collection, and navigation. However, full autonomy in robots poses a lot of challenges particularly in complex tasks such as search and rescue, harvesting, surgery among others. A fully autonomous robot may need very complex algorithm that is computational and energy demanding to cope with varied situations. Furthermore, in changing environments, there is no guarantee that the system will be able to accurately operate without human help hence exposing the robot and the environment to a lot of uncertainties that may lead to damage of the environment and or the robot itself. High fidelity tasks like surgery, search and rescue where human life is involved, may not be entirely achieved by autonomous systems as any slight failure may cost life thereby defeating the reason for the introduction of such systems. In agriculture for instance, continuous change of environment such as terrain, weather condition, morphology and color of the plants may lead to serious challenges in designing a system that can adopt to all the changes accurately and efficiently.

The introduction of human operator in the loop can assist in making decisions like safe time to overtake, slowing down when the vehicle in front shows brake lights or giving way to an ambulance. Moreover, this idea would bring efficiency in car hire business as the car would be easily tele-driven to a customer. Even though a lot of measures are always taken to curb cyber-attacks in both autonomous as well as remote controlled systems, autonomous systems may be at higher risk of attack than a remote operated system. This is so because unlike autonomous systems which in most cases assumed to be self-monitoring, in teleoperated robots, the system behavior is observed from the feedback and the operator can be able to detect any attempt of attack on the system early enough making it easier to make necessary adjustments to the system security on demand. Telecontrol of robots provides a promising alternative [5] that may soon overcome the numerous limitations of the full autonomy in robots. Indeed, regardless of the level of autonomy of the robot, there would always be a need for the input of a human operator in the robot operation loop [6]. The advantage of including human operator in the robot operation loop is the ability to provide numerous additional benefits like decision making corrections and the application of creativity to solve a problem efficiently.

Teleoperation of robots is a vibrant field that is gaining greater attention of researchers due to its applicability in many areas including industry, science, education, medicine, military, agriculture and entertainment [7]. In agriculture, for instance, a number of different tasks are performed in a given season. This may mean each task is assigned to a specific autonomous robot, a situation that may not be cost effective to the farmer. Introduction of human operator in the loop would be the most viable and economical remedy due to their adaptability and flexibility [8].

The manipulation and handling of robots remotely should involve reliable communication between master and slave [9]. The most prominent problem that hinders teleoperation is the communication delay between the operator and the remote environment which induces instability and poor performance in the control system [10]. Conventionally, in bilateral teleoperation systems, master robot is manipulated by the human operator by issuing commands to the slave robot which inturn is transmitted to the remote environment. The interactive force experienced between the slave and the environment is reflected back so as to allow the human operator to get the same experience of the remote environment locally. Quality of such systems is quantified using two main indices labeled as stability and transparency. Stability of a system requires that the closed loop system 'behaves' the same even under varried environmental conditions otherwise it is treated as unstable. For a transparent system, the separation medium between local and remote environment isn't realised due to cancelation of the the dynamics of the master robot and the slave robot [11]. Attention should therefore be paid in balancing these two indices as improvement in one may lead to significant deterioration of the other. Niemeyer and Slotine [12] asserts that force feedback could cause great instability in a system, hence obtaining a trade-off between stability and transparency is quite a challenge in bilateral teleoperation. Balance between transparency and stability has not been achieved in totality due to significant delay in the master-slave connection channel leading to poor quality visual feedback as well as increased error in slave position relative to the master. Many researchers [13] have focused their efforts to resolve the instability caused by communication delay problem using singular perturbation framework [14], dissipative theory [15], to mention a few.

Additionally, for efficient remote operation of a robot, it is vital for the operator to be aware of the environment around the robot, also called situation awareness, to enable him/her to issue informed and accurate instructions to the robot [16]. A limited view of the robot's environment makes it very cumbersome for a human operator to be aware of the robot's proximity to obstacles [17]. Situation awareness in human-robot systems can be improved through four ways; a) using a map; b) fusing sensor information [18]; c) minimizing the use of multiple windows, and d) providing more spatial information to the human-operator [19]. Moreover, introduction of virtual objects to compensate for the operator's inability to view the robot heading using the mounted camera especially due to objects blocking the viewpoint [20], may also help in knowing the robot pose. Three dimensional (3D) capture of the environment achieved through depth cameras and other sensors, like LIDAR, can also help in attaining operators awareness of the environment [16]. However, this approach leads to added cost and computational time. Employing multiple or omnidirectional cameras [20–22] that extend the field of view around the vehicle may improve the situation awareness and at the same time eliminate high cost as well as complex computation as opposed to use of 3D LIDAR.

A lot of research has been carried out on teleoperation in general including; bilateral teleoperation [23–26], teleoperation of unmanned aerial vehicles [27–29], teleoperation of industrial robots [30]. This work focuses mainly on the teleoperation of mobile ground robots which in most cases operate on very dynamic [31,32] and even hazardous environment [33,34], where human life can be at risk. The objectives of this paper are; a) to analyze the mobile vehicle teleoperation system architecture b) To discuss ways used by researchers in achieving presence experience in mobile ground robot teleoperation c) to give an overview of common communication protocols and wireless technologies used in teleoperation, their merits and challenges and d) to propose future direction in teleoperation of mobile ground robots.

This study is structured in the following format: Section 2 gives the reader an in-depth description of teleoperation architecture. In Section 3, the study focuses on the presentation of sufficient remote information to the operator, which is termed in this paper as presence experience. Section 4 discusses the applications of IoT/IIoT. Section 5 briefly discusses Human bias in teleoperation, while Section 6 gives a brief summary of the review work. Finally, Section 7 suggests future research in ground mobile robot teleoperation.

2. TELEOPERATION ARCHITECTURE

Teleoperation architecture consists of a number of components and control algorithms that makes the system work effectively. Among the components are; the execution infrastructure (that includes the processor), the communication infrastructure (that creates a link between the robot) and the operator. Others include a variety of sensors (speed, vision, position), different kinds of algorithm and the actuators. These can be put into three broad elements; i) the robot, ii) communication channel, and iii) the operator/user station as displayed in Fig. 2 below.

2.1. Robot system

The robot system, in this case, consists of the controller/processor system (MCU or Industrial computer), the actuators, sensors, encoders, base vehicle among many other components. This review will place emphasis on the control system since it is much more complex and the reader would gain more insight on the real system electronic architecture rather than the mechanical part that consist of the base vehicle. The design and development of electronic architecture for integration and control of the robotic system devices including actuators and sensors is quite a big challenge. All the devices within the control system compete to get the attention of the controller either to receive data or to pass back the feedback information. Introduction of a better architecture will ease the data collision and ensure smooth handshake between the controller and the devices attached to it as well as the remote operator. For proper control, the electronic architecture should be robust, reliable, easy to maintain and have the flexibility to allow addition of other modules [35]. The conventionally used centralized control system is being replaced by field bus control system which offers several advantages such as increased reliability and ease of maintenance [36]. However, the field bus control system is more

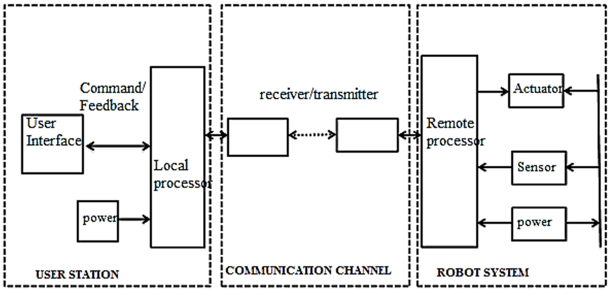

Fig. 2. Block diagram of teleoperation architecture.

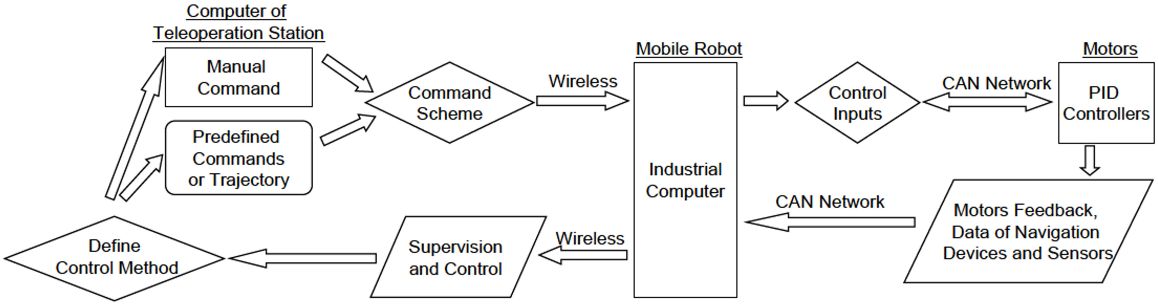

Fig. 3. Control flow diagram of CAN enabled robot teleoperation [39].

complex than the centralized system. Centralized system, on the other hand, suffers latency, loss of data packets and bandwidth limitations [37]. The use of field bus allows modular electronic control method which in the long run leads to flexibility and scalability of the system architecture. Controller Area Network(CAN) protocol based distributed technology is preferred due to its low cost of development, considerably high acceptance and success for embedded electronics in the automotive area [38].

Godoy *et al*. [35] designed and implemented an electronic architecture for a mobile agricultural robot using Controller Area Network (CAN) protocol [38]. Their research focused on the developed architecture, the wireless communication system for teleoperation and the distributed control based on CAN protocol and ISO11783. The test results indicated that the application of the ISO11783 standard based on CAN protocol provided an efficient platform to develop a distributed control system. Moreover, the use of electronic control units (ECUs) reduced the computational load of the industrial computer and simplified the data communication between the devices of the robot. Fig. 3 presents the flow diagram of a distributed control for a mobile ground robot. The system user is able to teleoperate the robot by either sending manual commands or using predefined commands to control the mobile robot. Commands sent by the human operator are transmitted to the mobile robot through a wireless link. Using the industrial computer as a gateway, the entire information from the operator is smoothly transmitted as control messages hence enabling execution of the commands and a feedback sent to the teleoperation station.

The safety of the robot system is vital since its damage or damage of its component is a complete failure of the teleoperation control objective. In this regard, it is in order that the robot control system is equipped with autonomy algorithm and obstacle detection sensors as well as automatic emergency stop as a safeguard against damage of the system in case of system failure or wrong command from the operator due to fatigue or lack of experience. This calls for the use of sensors to ensure robots safety. Fig. 4 gives a high level architecture consisting of autonomous obstacle/collision detection during vehicle teleoperation as well as the tools controller. The controllers and the obstacle detectors must have dedicated sensor system (for instance proximity sensors, contact sensors, speed sensors among others) that enable them to perceive the environment so as to autonomously make an informed decision on whether or not to execute a particular behavior.

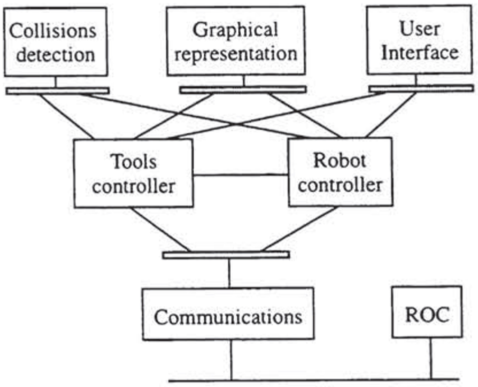

Fig. 4. High level teleoperation architecture with inbuilt collision detection [40].

However, with the human-in-the-loop, the popular sensors used in teleoperation are the visual sensors. These sensors are capable of providing the operator with a lot of information concerning the robot's environment. Researchers have used Charge-coupled device (CCD) cameras [39] as well as complementary metal oxide semiconductor (CMOS) [40] cameras to get information about the robot workspace. To enhance remote environment view, some researchers propose the use of stereo vision [41] since it provides depth information to the operator hence makes it easy for the operator to estimated obstacle distances and perform safe maneuver around them. The use of a combination of 3D photonic mixer device (PMD), which uses the principle of time of flight, and CCD camera to create 3D environment mapping was reported by [42]. This work aimed at taking advantage of the 3D visual effect to improve situation awareness which 2D cam-

Table 1. Characteristics of selected sensors used in robots based on the situation [53].

Situation	2D images	Stereo vision	Sonar
smooth surfaces (with visual texture)	Ok	Ok	Fails[a]
rough surfaces (without visual texture)	Ok	Fails[b]	Ok
close obstacles (< 0.6 m)	Ok[c]	Fails[d]	Ok[e]
far obstacles (> 10 m)	Ok	Fails[f]	Fails[g]
no external light source	Fails	Fails	Ok

a. specular reflection
b. no correlation
c. limited by focal length
e. limited by transceiver
f. poor resolution
g. echo not received

eras do not provide. Other than cameras, some of the sensors and techniques used for robot control include sonar sensors [45, 46], LiDAR [47, 48], LASER scanners and sensor fusion [49–52] to mention a few. Despite the fact that sonar sensors are relatively cheap, they suffer a lot of noise hence may give unreliable readings. Table 1 shows the characteristics of selected sensors used in robots.

2.2. Communication channel

The link between the operator and the robot is very vital in teleoperation since it is the primary medium which connects the operator and the robot environment. The absence of this channel means no connection between the operator and the robot and therefore no teleoperation. Effective communication requires consideration of a number of things including connectivity, routing, and Quality of service (QoS). Generally, it is the communication channel which is majorly responsible for the system delay and instability in a force feedback teleoperation [51]. It is, therefore, necessary that the communication channel is able to meet the desired QoS requirements including bandwidth, delay, jitter, reliability and at the same time maintain standard network resource utilization [52]. It is worth noting that the performance of a network also depends on the motion [53] and the distance between the two communicating centers, for instance, local-remote distance, robot-robot distance, robot-sensor distance or sensor-sensor distance. Teleoperation involves real time feedback and hence the need for a suitable protocol that will achieve feedback relay with minimal delay.

Many communication channels can be adopted for teleoperation including; internet, fiber optics, radio waves, infrared and wireless channels. Researchers have demonstrated success in the use of wireless technology to control robots. For example, [28] employed Bluetooth communication for command and data exchange between a cell phone and a mobile robot. However, due to limited range, the robot was confined to a particular radius of operation. Winfield and Holland [54] developed communications and control infrastructure for distributed mobile robotics. The proposed system made use of wireless local area network (WLAN) technology and Internet Protocols to establish connection between the local and remote stations.

Even though wireless communication has the advantages of relatively low cost and easy installation, it is slowly being overtaken by internet communication due to its robustness and ability to allow robot access and control from any part of the world with an internet connection as well as its independence on line-of-site between master and slave. However, despite these advantages, internet communication is prone to communication delay, packet loss, jitter, and connection blackout [55]. The most common internet protocols for data transmission include; transmission control protocol (TCP), User Datagram Protocol (UDP) and Real time Protocol (RTP) [56]. TCP protocol is a very reliable protocol used for transmission of data that require high fidelity, for instance, administrative data such as user login data [57]. Moreover, in TCP protocol data that is damaged, lost, duplicated, or delivered out of order by the internet communication system must be recovered. By guaranteeing delivery of data through retransmission of failed packets, this protocol offers reliable communication. The disadvantage is that its timeout is relatively longer for real time transmission [9]. In UDP, datagram is sent from the operator to the remote system and vice versa as fast as possible without considering the state of the network. In this case, the connectivity between the operator and the robot system is not maintained and hence it does not guarantee that the transmitted data packets will reach the destination. The delivery order of the sent data is also not guaranteed at the receivers end [58]. UDP is a real time transmission oriented protocol since it is designed for single-datagram exchange and it offers a faster access to the network. Real-time Transport Protocol (RTP) is a standard for real time delivering of multimedia data [59]. This protocol provides the mechanism for compensation of jitter and a way of detecting out-of-sequence arrival of data. In real time transmission, however, this protocol has a disadvantage related to buffer mechanism in that the time taken to buffer the data may introduce some delay.

The loss of packets and latency may lead to nonuniform force application to the remote vehicle since the data loss destabilizes the entire teleoperation system. Moreover, the transmission delay and the packet loss among other network characteristics are dependent on the number of nodes traversed by the data packet and the degree of the network traffic [60].

Table 2 gives a summary of selected research that applied wireless technology in teleoperation and their contribution in mobile robot control. Most researchers have achieved connections between the robot and the internet using Wifi as opposed to other available techniques eg

Table 2. Wireless technologies applied in selected robot teleoperation research works.

Wireless technology	**Range/ frequency/ data rate**	**Research work**			**Merits**	**Demerits**
		Institution	***Contribution***	***Author***		
Wifi IEE802.11a IEE802.11g	100-150 ft/ 2.4 GHz/ 11-54 Mbps	Technical university of Kosice, schlovac republic	Use of Android for robot control	[61]	• Uses lower power compared to mobile network • More secure as compared to Bluetooth • Portable • Offers slightly higher speed as compared to Bluetooth • Supports large number of users • Offers higher bandwidth	• Limited coverage area of about 150 ft • Installation cost is much higher than Bluetooth
		Hebei University of Technology Tianjin, China	Virtual reality in robot teleopreration	[62]		
		University of Essex Colchester, UK	Web-based control	[63]		
		Henan University Kaifeng city, China	Omnidirectional robot control	[64]		
		Technical university of ostrava, Czech republic	Augmented reality and ROS	[65]		
		University of the West of England	co-operative robotics	[54]		
		EESC, Av. Trabalhador São Carlen se, São Carlos	implementation of an electronic architecture for a mobile agricultural robot	[35]		
3G/4G mobile network (CDMA)	Global/ 800-1900Ghz/ > 2 Mbps	Vietnam National University, Hanoi	Multisensory-fusion	[66]	• Unlimited range • More secure • Higher bandwidth	• Highest power consumption • Costly
		National University of Singapore, Singapore	Immersive telepresence in on-road vehicle	[67]		
		Xian University of Technology, China	Use of 3G and GPS in Rescue robot control system	[68]		
		Sapienza University of Rome, Rome, Italy	IoT and long range robot teleoperation	[69]		

		Philadelphia University, Jordan	Remote sensing and robot teleopreration based on GPRS	[70]		
		Universidad Rey Juan Carlos, Madrid, Spain	A simulation system to control a mobile robot using a cell phone	[71]		
		Waseda University Japan	Interactive security guard robots, operated with a mobile phone	[72]		
Bluetooth	33 ft/ 2.4 Ghz/ 1.5 Mbps	Mokwon University, Korea	Touch-based Control	[28]	• Low cost and easy to setup • Lower power consumption as compared to wifi • Portable	• Low range of up to 400m • May be affected by obstacles • Offers low data exchange speed • Supports limited number of users Offers low bandwidth
		Middle East University, Amman, Jordan	Smart phone control and path planning	[73]		
		University of Guelph, Canada	network-enabled teleoperation system with a wireless mobile robot	[74]		

Bluetooth and mobile network. This may be due to better range as compared to Bluetooth. Even though mobile network has much wider range than Wifi, there is a trade-off between the range and other factors including ease of setup, maintenance, security and energy consumption of the system. This could be the reason why a good number of researchers opt for Wifi method over mobile network. Generally, it can be clearly seen that the technologies have their strengths and weaknesses. This makes it possible for one technology to complement the other. It is therefore prudent that before one decides on which technology to apply, they should analyze their project and the best individual technology or even a combination depending on what the project aims to achieve. Care should be taken when combining technologies as the element of cost may rise considerably.

2.3. User station

User station, also called operator workstation or base station, is the space/interface from which the robot is operated remotely. The interface used by the operator to control the robot is multimodal and comprises at least one display for image or sensor data visualization [21]. To command the robot in normal teleoperation, foot pedals, steering wheel, joysticks, computer keyboard or touch devices are employed [6, 78, 79]. The robot may be some distance within the view of the operator or at a long distance entirely out of sight of the operator. In the latter case, the operator is forced to strictly rely on the feedback from the remote environment which may be visual or physical. At the same time, the operator must have an interface that can allow easy reception of the feedback and issuance of control commands. In remote operation, the main source of feedback is the visual system that may contain single or multiple cameras. Images captured by the robot camera are displayed on a screen with some additional data such as robot speed, battery level, location from GPS data among others [6].

Although monocular vision is less complex, relatively less expensive and consumes minimum computational time, stereo vision [21] which is much more complicated is preferred since they provide additional information about depths of individual objects in the image [77]. Authors in [75] developed a novel model of teleoperation by employing sensor fusion and web-based tools for robots environment display. The designed interface allowed the operator to not only issue commands to the robot but also dialog with the robot by asking questions and receiving answers from the robot. Experiment showed that the use of operator-robot dialog and sensor fusion data display allowed easy teleoperation of the system even by novices with no experience in teleoperation. The same authors in another project [78] developed sensor fusion display and a suite of remote driving tools for teleoperating ground robot. In this work, other than the robot-operator dialog and sensor fusion display, they included computer vision, virtual interaction using gestures and personal digital assistant (PDA) for vehicle teleoperation. The developed remote driving tools were proven to be user-friendly, adaptive and required little training. Moreover, since the system was web-based, it could be used from anywhere as long as the user was able to access internet and had the right to use the system.

In remote teleoperation of robots [6], the use of direct operation is prone to problems like loss of situation awareness, untrue judgment of attitude and failure to detect obstacles. For easier control, the operator should visually feel immersed in the robot environment with sufficient and smooth video information feedback.

A number of researchers have achieved the concept of visual immersion using head-mounted display (HMD) device [81, 82]. HMD enhances operator's visual perception and significantly improves the sense of depth [81]. In this way, the remote operator can make informed situational judgment and effectively control the robot based on the stereo video streams. Kot and Novák [80] used Oculus Rift HMD to display stereovision images to the human operator. The outstanding characteristic of this project was the use of screen situated in the user station to reduce the nausea and/or eye-strain experienced when images from the robot environment were directly fed to the HMD device. To assist the operator during manipulation tasks a 3D model of the robot was rendered on the screen. The system was successfully tested, and the results revealed that the use of oculus rift HMD improved the operator's perception of the robot environment hence enabled the operator to effectively control the robot. Despite the success of the system, the low resolution of the Oculus rift device posed problem on image clarity. The initial objective of oculus rift HMD development was to aid in gaming and display of virtual environments. Its dual display feature gives the operator depth sensation through the stereo vision and provides immersion in a three-dimensional word hence enhancing the operators feel of presence in the remote environment [82].

The control of the pan and tilt angle of the remote stereovision camera is important to realize an even wider field of view of the camera. However, the unsynchronized motion of the cameras and the HMD leads to poor display and hence reduced clear perception of remote environment. This means that the yaw and tilt angles of the devices must be synchronized [79]. Despite the good results posted by HMD, in some cases the delay between the head orientation, the actual movement of the pan-tilt mechanism and the video frame update may lead to motion sickness, discomfort, and degradation of operator's perception [83]. Moreover, the head-mounted display may be heavy to wear and exhausting for the human operator as well as deteriorate vision-motor performance due to sensory conflict [86, 87]. With this idea in mind, [86] developed and evaluated new methods for robot motion and camera orientation control through the operator's head orientation with emphasis on the use of non-immersive devices. Results demonstrated that the camera control by use of non-immersive head orientation has the potential of improving the intuitiveness of robot teleoperation interfaces, particularly for novice users.

Many researchers have endeavored to realize the best human-robot interface since this is the only way the operator is able to visualize the robot environment hence effectively control it. Because of space limitations the reader is referred to the following references [89–96] for an in-depth coverage of human-robot interface for vehicle control and end effector manipulation. Table 3 lays down the main objectives, merits, limitations and outcome of selected research on teleoperation.

3. PRESENCE EXPERIENCE IN TELEOPERATION

Research and development in the robotics field today are geared toward ensuring that the operator feels physically present [97, 98] in the robot environment. Lack of situational awareness by the operator combined with too much cognitive load of various information sources presented to the operator when carrying out teleoperation task, impacts negatively on the human operator's performance [97]. Mental fatigue can be minimized by fusing information into a single view and provision of elaborate spatial information about the robot [19]. The feeling of presence in the robot environment gives the operator a conducive environment to understand the robot's situation hence effectively and efficiently teleoperate it. Unlike single sensation, the addition of multisensory inputs has been confirmed to have positive effect in creating a feeling of immersion and presence [98] for instance a combination of visual, audio and tactile feedback offers better presence feeling than a single increased photorealism of visual feedback [99]. Several researchers have proposed immersive interfaces with the objective of improving operator's situation awareness and telepresence using haptic, visual and auditory feedback for indoor and outdoor robots [100]. The efficiency of teleoperation is two tire; operator's situation awareness of the robot environment and management of transmission delay. The following sub-sections focus on the use of force feedback, virtual reality, augmented reality and mixed reality techniques to realize immersion in the remote site and the use of force feedback to mitigate effects of transmission delay.

3.1. Virtual reality (VR) in teleoperation

According to [101], VR is a technology that allows a user to view a virtual environment from any angle and interact with objects that make up the environment. Teleoperation efficiency is heavily affected by the virtual contact between the operator and the remote environment. When the human operator gets easy access to detailed information of the robot's environment, his/her capability to make quick and viable decisions is enhanced [102]. Virtual reality based teleoperation is achieved by the operator implementing the real robot control through manipulation of a 3D robot in a virtual environment. Through this, the operator greatly enhances his situational awareness and at the same time reduces or entirely eliminates the impact of communication latency thereby maintaining teleoperation efficiency [103]. Indeed, VR is capable of compensating large time delays since the virtual control is always less sensitive to temporal feedback delay than direct control [104].

The primary source of information of robot's environment for the operator in a teleoperation system is the camera(s) or sensor(s) mounted on the remote robot. Equipping the robot with a vast number of sensors or cameras has the advantage of increasing the operator's awareness of the robot environment. However, this has the disadvantage of increasing the computation load of the processor as well as raising the cost of the system. Moreover, considering that the operator needs real time feedback, a lot of sensor information may suffer packet loss due to limited bandwidth as well as network latency. To avoid overloading the system with a lot of cameras, most researchers propose the use of stereo vision and virtual reality [6, 81] that create a sense of depth of the remote environment to the operator rather than use of 2D camera views. The depth information not only aids in situation awareness of the robot surrounding but also help the operator in speedy and easy decision making [105] due to reduced cognitive workload.

As mentioned in the previous paragraph, virtual reality has the ability of positively dealing with communication delay. This advantage has prompted some researchers [82, 108, 109] to work on this field in an attempt to realize even greater efficiency in teleoperation of mobile robots. Cheng-jun *et al*. [107] designed a novel teleoperation system with a model of hierarchical control. A virtual environment was created using visual C++ and OpenGL to create operators sense of immersion and enhance his/her interaction with the remote robot. To enhance video transmission speed, a multi-buffer and multithread technology was implemented. This technology smoothened image transition hence improved the video quality. Virtual reality based teleoperation gives the operator a platform to control the robot directly from their 3D model, hence facilitating the prediction of all kinds of operations that could affect the robot or its environment [108].

With the introduction of head-mounted device like the Oculus rift, sonny play station VR and HTC Vive, teleoperation in several fields have been made much more effective [82, 110, 111]. Stereoscopic images from stereovision cameras attached to the virtual reality devices can significantly help with complex task manipulation. However, without an acceptable 3D rendering, the images may lose meaning [65]. For immersive robot control, the system should be able to appropriately employ the sensors mounted on the remote robot and effectively supply a display mechanism that will create immersive visualization to the operator. To achieve immersive telecontrol, [110] created a system to visualize robot environment map on a virtual reality device using point cloud data from a depth camera. Robot Operating System (ROS) was used to develop the robot control algorithm. The use of ROS facilitated implementation of communication between the robot and the user (VR device) wirelessly (see Fig. 5). From the experiments, the authors concluded that the point cloud data enabled the human operator to control the robot while clearly recognizing its environment through the VR device.

Integration of path planning algorithm with the virtual reality immersion is very important since it not only improves the control of the robot by the operator but also ensures robots autonomy to avoid obstacles. Ibari *et al*. [108] developed a teleoperation system for remote operation of mobile robot using virtual reality with integrated path planning method to improve robot control. This sys-

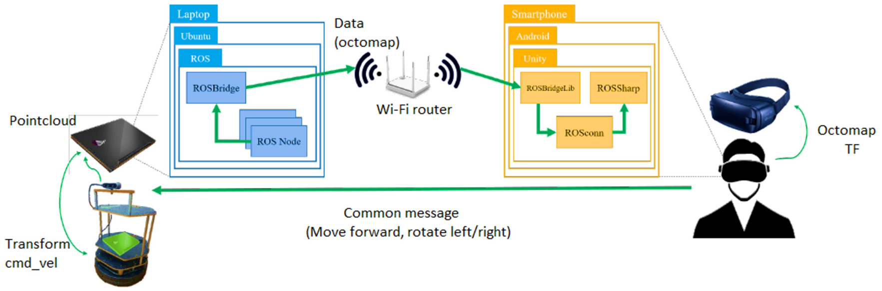

Fig. 5. Hardware and software architecture of VR teleoperation system [112].

tem, just like the one presented in [110], comprised of a virtual model of the robot's environment and wireless communication network.

The difference was the absence of HMD and the use of monocular camera to capture the robot environment. Experimental results confirm accuracy and stability of the system for robot teleoperation, Moreover, since the system was internet based it offered the advantage of being accessed from any machine connected to the internet.

One of the areas of application of telerobotics is in the search and rescue task in disaster scenes. The conditions in a disaster scene are mostly dangerous and hardly accessible. However, with all these hurdles, the rescue team must move in with speed to raise the chances of saving lives of survivors who may be trapped among the debris. Use of robots in these scenes will help in the evaluation of the hazardous area in the shortest time possible [113, 114] enabling the rescue team to make timely decisions in their operations. Telecontrol system of robots in this field must, therefore, be full proof to ensure easy access to the scene and quality environmental information. To achieve this, [113] proposed an immersive control system of a search and rescue robot (SAR) using an HMD with an integrated head-tracker. The introduction of this device was aimed at endowing the operator with the capability of perceiving the robot world in three dimensions (3D). Using the head tracker, the operator was able to control the SAR motion. Simulation results demonstrated significant improvement in user situation awareness due to depth perception when using the HM. However, the authors reported the longest time (634 seconds) when using the yaw control which they attributed to the sudden change of orientation of the robot causing confusion to the operator.

The growing research and technological innovations coupled with the ever-increasing telecommunication efficiency offer a very fertile infrastructure for telecontrol, telemaintanance and telediagnosis services in the field of automation technology. The availability of 3D modeling tools like World Toolkit (WTK) [114] among others has also made teleoperation easy, allowing the operator to predict the reaction of the remote robot from the behavior of the model. WTK, which has a frame rate of between 5 and 30 fps, is one of the object-oriented *real time* development environment. By integrating virtual reality technique in the user interface design, authors [115] were able to develop a system for efficient remote telecontrol of MERLIN (**M**obile **E**xperimental **R**obot for **L**ocomotion and **I**ntelligent **N**avigation) vehicle. The user-friendly operator-robot interface allowed visualization of the remote sensor data that gave the operator good situational awareness of the vehicle environment. The authors employed WTK modeling tool to achieve the remote vehicle virtualization and bring the robot's environment closer to the operator.

3.2. Augmented reality (AR)

Augmented reality is the overlay of digital content on the real world environment. Azuma *et al.*, [116] define augmented reality as a system that supplements the real world with virtual/computer-generated objects that appear to coexist in the same space as the real world. The general idea here is that the task of an operator is made easier and more compelling, by the fact that original information is augmented in some way by overlaying digital graphics or text. In this way, AR brings to the user enhanced representation of a real environment by integrating it with a virtual image or data. The virtual or digital objects range from images, videos, or other interactive data. Unlike virtual reality that presents only digital objects to the user, this reality gives the user additional content that allows him/her to clearly understand the environment.

Augmented reality is applicable in many fields to enhance the user's view of the real environment including; navigation and tourism [117], architectural construction and renovation [118], gaming and entertainment field [119] among others. In the field of robotics especially teleoperation, researchers have adopted this method in realizing feeling of presence in the remote environment. A novel Man-Machine Interface (MMI) that allowed advanced-level telework, using augmented reality was presented by [120]. The primary uniqueness of this system was anchored on two modes; perception and interactive modes. The perceptive mode was achieved through the use of a large screen that provided stereoscopic video and augmentation of the reality that offered a sense of presence to the operator. Interaction mode was presented using optical tracking system that allowed the operator to freely interact with the remote robot.

Stereoscopic vision improves the operator's feel of presence and improved understanding of the remote environment structure and approximate distance to surrounding obstacles. Despite being computationally efficient, 2D view of remote environment suffers a number of limitations including misjudgment of spatial localization, lame comprehension of remote layout, size and shape of the object as well as the distance of the object from the robot. This misjudgment may mislead the operator to issue wrong command to the robot resulting in collision. Stereoscopic presentation of the remote environment, therefore, offers an excellent alternative to monocular vision. This idea was adopted in the work of Livatino *et al.* [121] where laser range data was augmented on a stereo image of the remote environment. This technique allowed the operator to intuitively comprehend obstacle proximity to the robot and to respond accurately within a short time since the cognitive load of predicting distance is eliminated by the availability of the augmented laser scan image. Fig. 6 shows snapshots of the different processing phases as they appeared during one of the pilot trials of the system. The

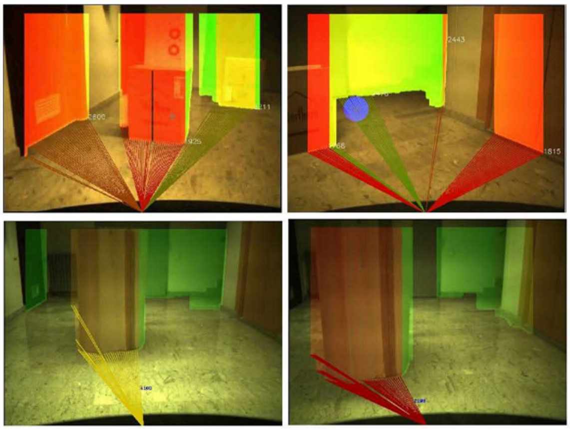

Fig. 6. Laser range image augmented on real remote environment image [123].

result of teleoperation of a real robot located thousands of kilometers away proved the feasibility and simplicity of the presented technique.

Other research works that have studied and applied augmented reality in robot teleoperation include; study on semi-autonomous mending robot [122], use of see-through head-mounted display and a head-mounted camera [123] to detect and tracks encoded message from the robot, system for telerobotic inspection and characterization of remote environments [124] among others.

3.3. Mixed reality (MR)

Milgram and Kishino [125] defined mixed reality environment as an environment in which real world and virtual world objects are merged together and presented within a single display. The merger of real world and a 3D virtual environment enhances the operators feel of presence as he/she is able to comfortably study the environment before issuing commands to the robot to perform a particular task. Mixed reality and augmented reality terms are always used interchangeably by some authors, however, there is a thin line separating these two techniques. In AR, a virtual environment is overlaid on the real world whereas in MR the virtual environment is anchored in the real world and the operator can interact with the virtual environment. The increased computational and graphical power of computers today has resulted in a significant increase in application of mixed reality systems [116]. The concept of mixed reality does not only help the researchers in managing the problem of latency in teleoperation but also aid in handling other challenges, for instance, the inability of the operator to see the borders of the remote vehicle/robot during teleoperation. The lack of clear vision of the vehicle borders poses greater danger to the vehicle and/or its surrounding particularly when navigating through narrow passages. Virtual visualization of the vehicle proposed by [126] gives a satisfactory solution to this problem. In this work, the virtual image of the vehicle's border and the wheels was overlaid onto the transmitted images from the remote environment and displayed through HMD. The availability of virtual boundaries offered the operator awareness of the exact vehicle position while HMD created an immersive experience which improved the operator's ability to control the vehicle through narrow passage (Fig. 7).

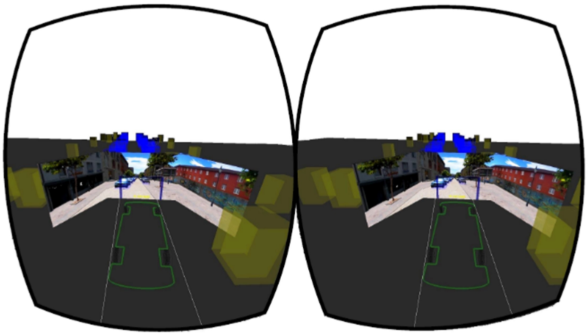

Fig. 7. Navigation through narrow passage by visualizing virtual vehicle border through HMD [128].

Another approach to achieve mixed reality and create a better remote environment awareness was presented by [127]. In this study, the authors developed and implemented a mixed reality user interfaces that integrated both 3D and 2D visualization of a remote environment for robot teleoperation. Preliminary tests showed evidence that the 3D mixed reality representation provided an improved teleoperator interface compared to 2D maps. This system was however complicated as operator had to wear special glasses having similar polarization filters as the projection to gain the stereo effect, the absence of which would lead to insufficient feel of presence.

Use of an interface with sufficient information other than the limited information from the sensors attached to the robot is of great importance. It must be remembered that over-reliance on the sensor information during teleoperation is not recommended as the data from the remote site may suffer delay causing serious instability in the system. Predictive displays offer a feasible approach to deal with these challenges. Achievement of an artificial exocentric view through the use of predictive display enhances the situational awareness for the human operator in teleoperation scenarios. This idea was implemented by Sauer *et al.* [128] in a bid to create awareness of the situation of robots without over-relying on the sensor feedback from the remote site. In this work, a virtual-master robot was overlaid on the real image of the remote site captured by the camera installed on the real robot on the site. By issuing commands to the virtual-master a trajectory was generated for the real robot, which was executed by the physical robot after a certain time. This helped the operator to predict the orientation and position of the robot before execution of the commands hence enabling him/her to efficiently control the robot to avoid obstacles and achieve tasks effectively.

Most mixed reality teleoperation approaches face poor performance on vehicle lateral stability during telecontrol especially when HMD device is used. The operator, in most cases, is unable to see neither his hands nor the steering wheel through the HMD device. It is therefore proposed that for the lateral vehicle stability to improve, there is a need for additional virtual reality element through dynamic visualization of steering wheel, operator's hands and position of the pedal in a mixed reality space [126]. Table 3 gives a summary of techniques used by selected authors in an attempt to achieve immersive teleoperation.

Based on Table 3, a good number of researchers have employed the use of HMD and stereo vision to achieve 3D representation of the remote environment. Moreover, sensor fusion has also been adopted to reduce the cognitive workload on the operator. There is also the use of 3D model of the robot used particularly in solving the problem of transmission delay in teleoperation. However, in the cited literature, multiple view, computer vision and sensor fusion techniques have not attracted the use of 3D model of the robot. This could be because 3D models require higher computing resources to run hence may eventually lead to higher cost of the entire system, a factor that should be avoided to make the system commercially viable. Even though multiple views would allow the operator to get a feel of presence in the remote environment, it bombards the operator with a lot of information hence exposing them to much higher cognitive workload. It must be remembered that during teleoperation mission, there are situations that require quick decisions to safeguard the remote environment as well as the robot. Having multiple views may cause delay in decision making and action since the operator has to analyze all the views before deciding the final command to issue. Notably, laser, sonar and stereo vision sensors play a major role in the operator feedback techniques. These sensors provide the operator with both proximity data and depth information hence allowing the remote operator to make informed judgement about how close an obstacle could be. Both sonar and laser sensors provide similar data and therefore may not be used simultaneously. However, for accuracy, laser sensor would be the most appropriate as the sonar sensor data is affected by environmental echo since it depends on sound reflection to estimate the distance. Maps are very vital in robot teleoperation especially when the operator would wish to feel present in the remote environment. Most authors have employed the use of maps as can be observed in Table 3. Whereas greater percentage of the cited work have employed 2D maps VR technique has only employed 3D maps. caution must be taken when selecting the kind of map to be employed since increase in map dimension leads to increase in computational requirement of the system. VR, MR, and AR are good techniques aimed at achieving effective and efficient robot control. Readers should understand that despite the fact that we have discussed these techniques with focus on ground mobile robots they are open to application in other types of robots as well. Other than MR and VR, AR has an advantage in that it gives additional information that aid the operator during decision making. This is a factor that has made AR stand out over the other two techniques. However, all these techniques are geared towards one main objective of improving the efficiency and effectiveness of teleoperation. As demonstrated in Table 3, it is also worth noting that some of the systems are open to any application making it easy to only do a slight modification to suit particular application.

3.4. Teleoperation with force feedback

Availability of good quality and accurate multimodal sensory feedback from the teleoperator is essential for creating a sense of presence to the human operator making him/her feel immersed in the robot's environment. With the presence of inevitable time delay in teleoperation, that may be variable or constant [129], the human operator within the loop may sometimes get poor feedback quality which hinders him from giving correct instructional commands to the remote robot. This may lead to collision of the robot with obstacles in case the autonomous control system is unavailable or fails. Transparency, which is the ability of the system to provide the operator with the feel of the remote environment [130], is an important feature of bilateral teleoperation system with force feedback. Researchers in teleoperation field [135–137] have proposed the use of force feedback to enable the human-operator to feel present in the remote environment; a situation referred to as telepresence, as well as improved stability of the teleoperation system. The stability of a bilateral teleoperation system can be severely affected by a transmission delay even as low as 100 milliseconds [134]. Moreover, [135] confirmed from their work that packet loss and jitters lead to non-smooth application of force to the remote robot since the loss significantly destabilizes the teleoperation system. In order to maintain smooth force feedback from the robot, the dynamics of the remote environment must be taken into consideration and the system needs to be adaptive to deal with the ever-changing environmental conditions. Adaptive control is vital as it transmits the right force as felt by the remote robot back to the human operator [138] making him feel present in the robot environment.

The use of worst case scenario, where the developers only considered the maximum roundtrip time to design a controller in an attempt to eliminate jitters was disputed and reported to be unstable by [139]. In other research,

Table 3. Attempts by selected researchers to improve situation awareness and reduce cognitive work load on human operator during teleoperation.

Technique	3D Model	Real image	HMD	Map	Sensor	Remark	Area applied	Author
Multiple view	N	Y	Y	N	Sonar, stereo camera	Achieved 60% effectiveness in path guidance and spraying	Agriculture	[136]
	N	Y	N	Y	Sonar, stereo camera, Ladar	Improved user perception and efficient command generation	Remote driving	[105]
Sensor fusion	N	Y	Y	Y^2	Sonar, stereo camera	Facilitated environment assessment	Open	[18]
	N	Y	N	Y^2	Sonar, stereo camera	Sonar data allowed operation in low/no light areas	Open	[75]
Computer vision	N	Y	N	Y^2	Camera/laser	User adaptive, can be used anywhere	Structured environment	[78]
Virtual reality	N	N	Y	Y^3	Depth camera	Reduced cognitive load	Exploration	[110]
	Y	N	N	N	CMOS camera	Allow direct control from 3D model	Open	[108]
	Y	N	Y	Y^3	Stereo vision	Successful identification of objects of interest	Search and rescue	[113]
	Y	N	N	Y^3	Laser/camera, ultrasonic, odometer	Prediction of the position and orientation of the real robot	Mobile robot for outdoor environment	[115]
	Y	Y	N	N	Web Camera	Easy robot control due to known set delay	Indoor operation	[106]
Augmented reality	N	Y	N	Y	Laser/stereo vision	User able to intuitively comprehend object proximity	Open	[137]
	N	Y	Y^{st}	N	Augmented reality mast	The optical See-through HMD allow superimposition of information on the swam of robots	surveillance, reconnaissance, hazard detection, and path finding	[123]
Mixed reality	Y^{2D}	Y	Y	N	LiDAR, camera, IMU	Reduced workload by 5%	Urban driving	[126]
	N	Y	N	Y	Stereo vision cameras	Ease of control in 3D virtual environment	Search and rescue	[127]
	Y	Y	N	N	camera	Used PUI to achieve an artificial exocentric view	Open	[128]

Y - available, N - not available, 2 - 2D, 3 - 3D, st – see through, PIU - Predictive user interface, IMU - Inertial measurement unit, HMD - head mounted display

authors have attempted to mitigate the effect of jitters by introducing buffers to temporarily store the received data [135]. Introduction of force feedback in telecontrol of robots dramatically improves the operator performance by reducing collisions through maintenance of safe distance between the robot and obstacles [140]. Lim *et al.* [141] designed and implemented internet based teleoperation system for a mobile robot with a force feedback. In their work, a virtual force was generated and fed back to the operator to improve the reliability of the teleoperation, in that the interaction between the slave and the environment was reflected to the operator as a form of impedance. The virtual force generated was dependent on the distance between the robot and the obstacle as well as the approaching velocity of the obstacle based on the data obtained from the ultrasonic sensor. Experiments carried out on the system demonstrated that the haptic reflection significantly improved the performance of the system.

To realize better feedback and control during latency and induced network outage, [142] implemented an event-based controller with force feedback for robot teleoperation. The idea used in this work was slightly different from other force reflection systems in that each motion command of the joystick is treated as an event. The system consisted of master haptic device, slave robot and a communication network. Two PCs were used, for operator (client-pc) and for the remote robot (server-pc). Experimental results indicated that the slave robot successfully followed the master device motion and communication delay had insignificant effect on the performance and stability of teleoperated robot.

Sophisticated operator-machine interfaces have been reported to improve significantly the overall performance of teleoperation system when the number and quantity of data from the remote environment are augmented [143]. Through force feedback, a lot of control errors and stress on the human operator can be reduced significantly leading to smooth, tireless and efficient control of the robot. The application of force reflection on a system not only assists the operator to be conscious of the impending obstacle but also the contact force with an object [144]. The remote robot can be equipped with contact or pressure sensors to generate feedback contact force. The use of ultrasonic sensor for distance measurement has been widely used. However, these sensors have several drawbacks including poor angular resolution of about 25 degrees and effects of sampling rate of about 50ms due to sound speed which is relatively low. Moreover, it suffers multiple reflections of sound waves leading to overestimation of distance [145].

The use of laser scanners for path planning is gaining attention due to its precision. [146] Estimated the distance from obstacle using laser scanner and applied the data to generate repulsive force that is fed back to the operator. The author concluded in their experiment that the force feedback and the augmented perception of the robot's environment greatly reduced the vehicles collision with obstacles. In other related work, [145] presented a passivity controlled scheme for mobile robot. This control scheme was based on virtual mass with guaranteed passivity. Unlike in [145] where the vehicle was restricted from getting into contact with the obstacle, [144] controlled a mini-rover over the internet with force reflection. However, in this case, the rover was equipped with a force sensor that sent a feedback signal to the operator once the vehicle was in contact with an obstacle. This is the same force that was fed back to the joystick and felt by the operator. The reliance on contact between the robot and the obstacle is quite dangerous since the impact may lead to the damage of the robot particularly when the approach velocity is high. In such cases, the robot needs to be equipped with some level of autonomy to enable it make decisions in case the operator is not able to visualize the environment appropriately. Instability of bilateral teleoperation with force feedback has been widely studied. Since this is a very huge area and this review may not discuss it exhaustively, the reader is referred to the following resources for more coverage [133, 149–152].

Fig. 8. Mobile robot teleoperation system based on IoT [72].

4. APPLICATION OF IOT AND IIOT IN TELEOPERATION OF MOBILE ROBOTS

The Internet of Things (IoT) is a system of related computing devices equipped with unique identifiers and having the ability to exchange data over a network without human interaction. IoT allows sensing and control of 'things' remotely within the network infrastructure, hence enabling efficient integration of the physical world into device-based systems leading to significant improvement in efficiency, accuracy and profits as well as partially or fully eliminating human intervention. It was projected that the worldwide market of internet of things would rise up to around $1.7 trillion by 2020 [151]. Currently researchers in the robotics field are exploring use internet in robotics both for conventional and industrial applications hence coining the new terms Internet of Robotics Things (IoRT) and Industrial Internet of Things (IIoT). Uddin *et al*. [69] in their study introduced a long range internet connected robot teleoperation system which was IoT based.

The work was aimed at supporting the human operators during teleoperation of robotic systems in case the remote control devices lose the connection with the receivers. The setup of the system is as in Fig. 8. Although the system was able to successfully operate, it could only be operated "blindly" as there was no installed camera for visual feedback. In a separate work, [152] presented a simple framework to control mobile ground robots by employing a multi-touch gesture interfaces on handheld devices. To allow the operator have a view of the remote environment, an infrared (IR) camera was employed. The IR camera presented double-fold functionality, that is, to offer a gesture-based image monitoring system for teleoperation mode control and acting as a sensor for autonomous mode operation.

Recent growth in the mobile device market and advancement of technology has completely expanded the functionality of mobile devices from simple telephone

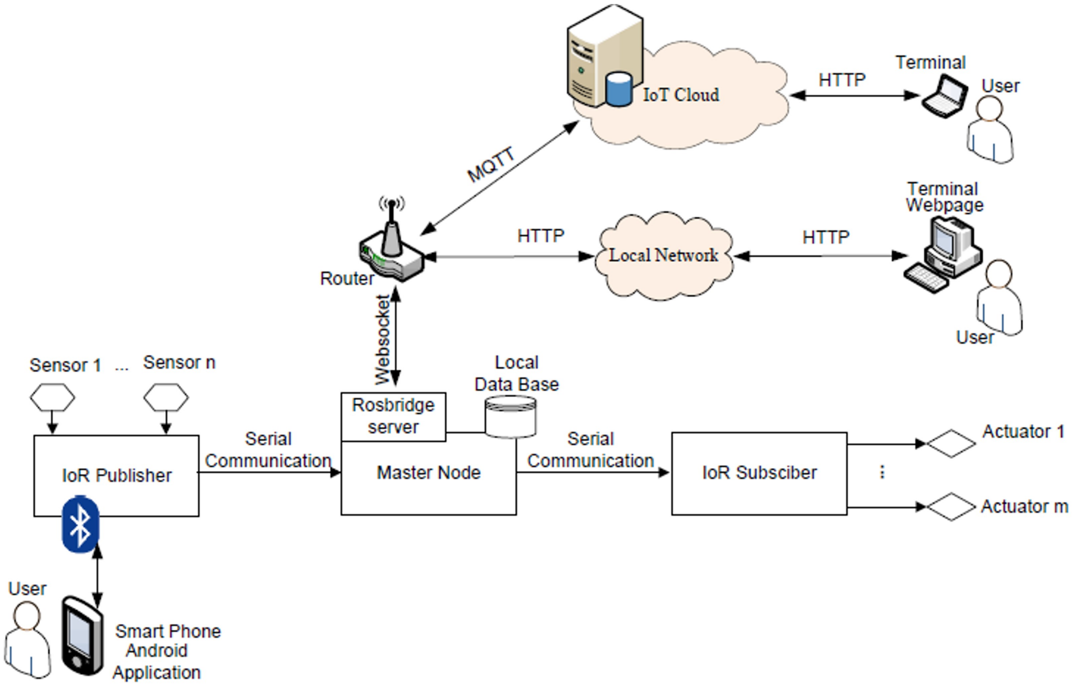

Fig. 9. System model for Internet of Robotics thing car [156].

conversations into portable personal computers running one or more operating systems. Their ability to not only use cellular phone networks, but also other networks like Bluetooth and Wi-Fi technology for data exchange with other electronic devices has made them a fertile ecosystem for IoT applications. [153] developed a platform for teleoperation of robot using android devices. The developed platform allowed remote interaction and control of robot through mobile device user interface display or voice. An ultrasonic sensor installed in front of the robot gave the operator feedback of how close the robot is from an obstacle hence change the course or stop the robot. Despite the success of this platform and ability to control it over the internet using any android based device, the experimental robot could only be controlled within operators site since the only feedback was range data as the robot was only equipped with the ultrasonic sensor.

An Internet of Things based Robotic Car Control system was developed by [154] in an attempt to create a collaborative control of the robotic car from internet connected devices. The system implementation demonstrated the real implications of Internet of Things with robotics in a novel form. However, the system had a limitation of a forced star topology network where all the data from a client to the robotic car or from the publisher to the IoT cloud had to be transmitted through the Master node. Fig. 9 shows a system model for the IoRCar.

Integrating IoT and robotics allow the robot to connect with other devices as a ‘thing’. This enables it to search and establish connections to other devices within the network while playing the role of information source or information consumer. Through information consumption the robot gets access to vital information from sensors or database to assist in critical decision making for task achievement. As an information source, robot within an IoT network considerably enhances collaboration between human and robot hence raising task achievement efficiency.

In a typical modern industrial environment one will encounter a set of machines working together to achieve a common goal. These machines in most cases are interconnected to share data and operate in tandem. Here, IoT target applications dealing with the realtime monitoring and even control of components of the robot system for instance; electrical systems, system vibration, and temperature among others. Several application fields [56, 157] have demonstrated advanced Technology that aim at achieving adoptability and human-robot friendly interaction in industrial applications. Widening the coverage area beyond the industrial production domain, a number of IoT applications have been presented on agricultural area monitoring [156], energy distribution platforms [157], solar and eolic plants [158].

Even though not much work has been done on integration of robot teleoperation and IoT/IIoT [161–163], we believe this technology will make a global interconnection of robots, smart objects interconnection with industrial machines, embedded electronic devices in buildings, among others hence creating a clear avenue for the development of advanced systems as well as applications.

Achievement of IoT/IIoT integration in robot teleoperation will rely greatly on the platforms [162] that are already available and those that may be invented the future research. The most commonly used platforms include; Pachube which is a real time open data infrastructure platform for IoT designed to manage hundreds of thousands of data points daily from companies, individuals and organizations worldwide. SenseTale is another very important platform that aggregates data from a number of sensors embedded on "things". The collected live data is sharable in social platforms easing ways of reaching a bigger population of individuals who would wish to visualize or use the data. Cloud based platform Nimbits allow individuals, devices and sensors to connect to the cloud. This enables easy definition of points and feeding of variable information into them. Last but not least, there is the ThingSpeak IoT platform which individuals use to store and even retrieve data from IoT interconnected devices using *HTTP* protocol via Local area network or wide area network. The main feature that makes ThingSpeak stand out is its feature that allow creation of new applications such as sensor data logging and location tracking applications. Moreover, it also simplifies creation of social network of IoT with real time data updates.

5. HUMAN OPERATOR BIAS

Tele-robotic systems have the ability to offer support to humans to achieve tasks in a number of applications. However, the overall output of the teleoperation process heavily depends on motor functionality as well as human operator's ability and skills [163]. The human operator influence on the system performance depends on a number of factors among which are discussed briefly in the following subsections. The reader should take note that some of these factors have been discussed in details in earlier sections and therefore will be briefly revisited for the purpose of understanding how human operator bias affect the entire process of teleoperation.

5.1. Situation awareness (SA)

One of the most critical factors in decision making by the operator squarely depends on how well the operator perceive the robot's environment. This is very useful when the operator is encountered by huge work load in variable control tasks [166, 167]. The relevance of situation awareness in a system with human in-the-loop may be witnessed especially during operations that involve a number of competing goals and simultaneous task that call for attention of the operator and allocation of resources. Situation Awareness Global Assessment Technique (SAGAT) [166] is one of the best tools for assessing the human operator's situation awareness. This technique has lent its usefulness in assessing situation awareness at different stages of autonomy [164]. SAGAT performs a detailed task analysis in a bid to formulate proper operational query for measuring the SA. This technique was employed by Scholtz *et al.* [167] to formulate questions to assess and analyse human intervention in autonomous off-road driving. It must be remembered that SA is very key in the operator performance even in simple task achievement.

5.2. Workload

The cognitive workload that the operator has to analyze and interpret during teleoperation has a direct bearing on their performance. A huge load may lead to lower performance as the operator has to take much time and other resources to achieve a simple task. There are several assessment techniques for multidimensional workload which aid in relating the perception of the cognitive load to the operator, performance, telepresence and proper design of user interface. One of the mostly used techniques is the NASA-Task Load IndeX (NASA-TLX). This technique has been applied in a number of teleoperation research work [164] to assess human cognitive workload and performance. generally, based on subjective ratings, workload experienced by human operator declines as the level of system autonomy rises. Moreover, the shorter the teleoperation tasks, the lower the workload. Substantial work on the application of physiological assessment as real-time indicators of cognitive workload has already been conducted.

5.3. Accuracy of mental models of device operation

The system design, expectations of the operator as well as the stimulus-response compatibility are very strong factors that may influence human performance during teleoperation of robots [168]. Main compatibility modes include movement, conceptual, spatial as well as modality [169]. Macedo *et al.* [170] asserted that matching interface displays as well as controls to human "mental" models has a number of merits including reduced mental transformations of information, quick learning and lower cognitive workload. Readers who are interested in studies focusing on mental model assessment may refer to the following literature [169, 171].

6. CONCLUSION

Mobile ground robot teleoperation system consists of three main components; the master, communication channel and the slave. Effective teleoperation is measured by the transparency and stability of the system. The exactness with which the slave tracks the position of the master forms the transparency of the system while the robustness of the system against external disturbance forms the stability of the system. The operator's ability to effectively and efficiently achieve remote task is influenced by the information he/she obtains from the remote environment either visually or physically as well as the reliability of the communication channel connecting the slave and master stations. This work has presented a substantial and simplified review of architecture that the authors have used in achieving teleoperation of mobile ground robots, the tools and approaches used to achieve telepresence including the use of head-mounted display, sensor fusion as well as force feedback devices. The use of HMD has been reported by a number of researchers to improve the feel of presence. However, the authors also reported limitations of this technology including creating motion sickness, some are heavy and the ones with better qualities are relatively expensive. Moreover, this review has discussed some of the communication channels and protocols employed to link the operator station and the slave station. Internet is reported to be one of the common channel with an advantage of making the teleoperation system reachable from any part of the world with internet connection. However, internet also poses a greater challenge since it is characterized by a lot of delays, jitters and data loss. Various wireless technologies employed in teleoperation have also been briefly studied in this work. Wifi is shown to be the most preferred wireless link compared with mobile network and Bluetooth. This would be associated with its ease of setup and relatively low energy consumption. Overall, the main challenges to teleoperation of mobile ground robot are communication delay and insufficient situation awareness of the operator. These challenges lead to instability of the teleoperation system hence reduce effectiveness and efficiency of the system.

7. FUTURE PERSPECTIVE

More research, is needed to improve the stability of teleoperation system, especially over the internet due to huge network congestion caused by significant traffic leading to serious delays and data loss. The need for a well-designed system capable of restoring signal strength for long distance teleoperation is of necessity. This will enable easy and efficient teleoperation and eliminate data loss over long distance. With the high rate of cyber insecurity, many teleoperation systems may encounter difficulties due to system hacking. It is therefore necessary that researchers focus some efforts on efficient and economical ways of dealing with security of teleoperation system especially the internet based teleoperation systems. Even though the security system should be made very complex to ensure system safety, simplicity of security monitoring from the operator's end must also be given a greater priority as this will leverage the operator the cost of hiring experts to monitor the system.

With the growing high speed internet availability, and the need to involve experts in collaborative robot operation, research should also focus on techniques of ensuring smooth coordinated teleoperation in a single-robot-many-operators system without limiting the operators to the conventional queue-system. Introduction of this will ensure that an expert is given priority such that he/she can be able to save a situation even when the current operator is still logged on. This technique will be very useful in applications like, medicine, search and rescue, underwater vehicles among other areas that may need quick expert intervention.

Among the wireless communication, Wi-Fi seems to be the common method that most researchers have adopted based on their ease of setting up and configuration. However, this technology faces the problem of range limitation and therefore cannot be applicable when a robot is required to operate within a wide area. Introduction of use of mobile network could be the solution to this since their coverage is global. However, very little research has been put forward employing this technique. The soon to be launched 5G network which will not only offer wide range service but also tremendously improve data transmission speed should set a fertile stage for research and application in teleoperation. Researchers should focus on the best architecture that will not only be simple to be set up and configure but also economical to use.

The use of multimodal interface in teleoperation has worked to some extent to make the operator feel present in the robot's environment allowing them to make decisions based on visual information. However, one area that has not been satisfactorily explored is a way to make the operator feel as if he is operating the robot from inside. The operator should therefore be able to feel for example the robot's vibration, temperature, sound among other necessary feedback. This will help mostly in applications in teleoperated taxis, which may require that the operator gets the feel of road bumps, inertial effect due to brake application or acceleration among others. This will ensure the comfort of the client hence the success of this venture.

Most literature in teleoperation focus on how well the operator would feel present in remote environment through several techniques like using HMDs as well as force feedback. In this case the operator has to analyze the robot situation to make decision. With the advancement of big data (BD) and machine learning (ML) techniques, researchers in robot teleoperation system should focus on the use of BD and ML techniques to develop robot teleoperation system in which the robot can learn its environment and advice the operator on the next action to take rather than the operator relying on his own analytical skills to control the robot. This in turn will reduce the cognitive workload on the operator as well as allow easy control of the robot even by novices.

The advancement in mobile phone technology has led to development of highly capable smart phones but at affordable prices. However, the applications of these phones in robot teleoperation has not been efficiently achieved due to low storage and processing capacity. Integrating mobile phone technology with cloud computing in a more economical way will aid in development of a fordable mobile based teleoperation systems which have much more capability than the currently available systems. Moreover, since one only need to have a smart phone, the system will attract a large number of users who will benefit from the system.

The use of maps in robot teleoperation is quite vital especially during robot localization. This requires simultaneous building of the map as the robot navigate and the feedback sent to the operator in real time for appropriate decision. However, this data is relatively bulky and requires a large bandwidth for transmission to the operator. To support large bandwidth, a lot of finances must be channeled to the service providers hence making the system economically nonviable. Moreover, bulky is prone to delays as well as loss during transmission. Future work should therefore be based on novel techniques of reducing the weight of this data so that a lower bandwidth can be used to transmit such data, further improving efficiency in remote control of the robot.

In addition, it has been observed that HMD has the advantage of making the operator get immersed in the robot environment and significantly improve his/her ability to control the robot. However, this device has some disadvantages including causing motion sickness, imposing heavy weight on operator and is expensive. Researchers should, therefore, focus on these disadvantages for much more economical, effective and comfortable presence achievement in teleoperation of mobile roots. It must be noted that the feeling of presence is not only due to the 3D visual feedback but also the force as well as the audio feedback. Achievement of all these feedbacks transparently is a big challenge bearing in mind the limited bandwidth. Focusing on this challenge in future work by introducing an economical, stable and user-friendly way of availing these feedbacks to the operator will improve the feel of presence hence much more efficient telecontrol of the mobile robot. Finally, to help reduce the cognitive load on the operator, future research should focus on sensor fusion of stereo vision data and range data in a synchronized manner to ease the control of the mobile robot for navigation and task achievement.

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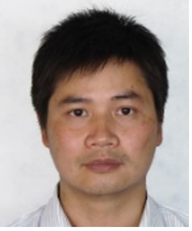
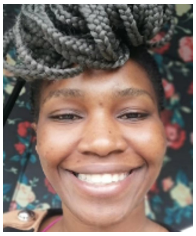
Samwel Opiyo was born and raised in Kisumu, Kenya. He received a B.E. degree (physics, majoring in electronics) at Moi University-Kenya and graduated with second class upper division in 2008. He then enrolled for an M.S. degree (electronics and instrumentation) at Kenyatta University, Kenya, where he graduated in 2015. He has taught digital electronics, computer programing and robotics-related courses in Catholic University-Kenya, Mount Kenya University and Moi University-Kenya. He is currently a Ph.D. candidate majoring in electrification and automation at Nanjing Agricultural University specifically dealing with teleoperation of robots. His areas of interest include human-robot collaboration, digital image processing, teleoperation of robots, and IoT.



Jun Zhou is a full professor at Nanjing Agricultural University. He graduated, in 1998, with a B.E. degree from the Agricultral Mechanization Department, Nanjing Agricultural University, China. In 2003, he received a Ph.D. degree in agricultral engineering, Nanjing Agricultural University, China. In the year 2005, he completed his Postdoctoral Research Fellow, in mechatronics engineering, Shanghai Jiaotong University, China. He was a Visiting Scholar, in agricultural engineering, Iowa State University, USA, in 2013. His research interests are agricultural robot, digital image processing and pattern recognition, automation for agriculture, equipments for precision agriculture.



Emmy Mwangi graduated with the second upper B.Eng. degree (control and instrumentation) from Egerton University Kenya in 2017. She is currently an M.Sc. candidate majoring in agricultural electrification and automation at Nanjing Agriculural University. Her research interests include agricultural robots, digital image processing and control systems.

Wang Kai obtained his Master's degree in mechatronics engineering from Changzhou University in 2012. He is curretly a Ph.D. candidate at Nanjing Agricultural University. His research directions are agricultural robots and robot navigation technology.

Idris Sunusi received his B.Eng. degree in agricultural engineering from Bayero University, Kano-Nigeria in 2009 and an M.Sc. degree in engineering (farm machinery) from Ahmadu Bello University, Zaria-Nigeria in 2016. He later joined the services of National agricultural extension and research liaison services, Ahmadu Bello University, Zaria in 2011 as an assistant lecturer/extension specialist. He has worked on the development of machinery for harvesting and processing of crop and is currently a Ph.D. research student in Nanjing Agricultural University, China. His research directions span dynamic control of electric vehicles, application of artificial intelligence in agricultural systems and automation of agricultural machinery.