

A Review on Emerging Technologies of Telepresence Robot Applications, System Design and Engineering Challenges

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Abstract:- A telepresence robot is a type of mobile robot that supports a human to achieve a sense of physical presence in a remote environment. A real time audio visual communication, mobility and interactive control is integrated within the robot. Early telepresence robot systems is based on manual teleoperation, through recent advances in communication and mobile robot technologies that increasingly merge adaptive motion and intelligent navigation improved system safety, usability and operational efficiency. This review is intended to study emerging telepresence specific studies in robots and challenges faced with mobile robot technologies. This review aims to cover concepts and developments to favour students and researchers to explore future research directions. The study is majorly done with scopus indexed journal articles and is also complemented with selected conference papers, technical studies and emerging work that address experimental platforms and application based developments relevant to telepresence robots and adaptive mobile robotics. This review is studied based on advances in navigation strategies, autonomy, perception, human robot interaction and system architectures. The paper explores current research trends, compares common existing approaches and highlights critical challenges such as autonomy and user balance, robustness in crowded environments and integration of intelligent decision making. This review also highlights the research gaps and future directions for the development of future telepresence robots with improved autonomy level and navigation capabilities.

Keywords: Telepresence robots, Mobile robots, Adaptive autonomy, Navigation, Human robot interaction, Artificial intelligence.

1. Introduction

Telepresence robots is a type of wheeled mobile robotic systems that allow people to be present remotely through a physical robot. Standard video calls or online meeting tools are means to interact with a person without any knowledge of surrounding environment, therefore a telepresence robot is used as it can move within an environment, observe surroundings and interact with people and objects. These capabilities makes it applicable in workplaces, hospitals, classrooms and public spaces where physical presence is important.

The early Telepresence systems constituted of robot movement controlled directly by the user through manual commands. This approach works in familiar and controlled environments where faults can be mitigated. This places a high mental burden on users and leads to navigation errors. In a crowded or unfamiliar spaces problems such as communication delay, limited environmental awareness and collision risks further reduce it's usability. Recent research has focused on introducing adaptive autonomy by which robot automates navigation tasks such as obstacle avoidance, path planning and environment aware motion whilst still allowing human supervision.

Telepresence robots are mainly studied in the field of Human robot interaction (HRI) or from social perspectives or they focuses on robot navigation techniques. Research areas also focus on adopting Robot operating systems (ROS). To understand the challenges faced in the application of telepresence system in a real time environment along with a comparative performance analysis of various commercial models is the objective of this review.

This review aims to address a system level overview of telepresence robots along side mobile robot technologies to get a deep understanding on adaptive autonomy and navigation. The objective of the paper is to bring together relevant journal articles and complementary studies to examine navigation methods, autonomy levels, perception techniques, interaction models and system architectures that can be directly applicable to telepresence robots. Importance is placed on practical design choices and integration strategies for real world deployment.

The paper is organized as follows, *Section 2* explains the review methodology and literature selection process. *Section 3* provides an overview of telepresence robot systems and applications. *Section 4* discusses navigation and motion control in telepresence robots. *Section 5* reviews mobile robot navigation technologies of telepresence robot systems. *Section 6* is based on adaptive autonomy and artificial intelligence techniques. *Section 7* focuses on human robot interaction and social presence. *Section 8* analyzes system architectures, middleware and integration. *Section 9* compares existing reviews and related survey works. *Section 10* identifies open challenges and research gaps. *Section 11* provides future research directions with *Section 12* to conclude the paper.

2. Review Methodology and Scope

Together with review of some mobile robot technologies and telepresence robots that enable adaptive autonomy and navigation, this review is planned in a structured and organized based on the system designed for a telepresence robot. The selected literature discusses navigation algorithms, autonomy techniques, human robot interaction, telepresence system design and real world applications. The review of some mobile robot technologies though unrelated to telepresence specific robot applications was done to present existing algorithms in case it makes a use case in telepresence robot future research.

Adaptive navigation is a dynamic method employed in robot to modify its path planning and movement behavior in response to environmental changes, sensor feedback or past experience, thus supporting an autonomous framework. To understand adaptive navigation and autonomous decision making for a telepresence system, paper [1] constitutes the methods to adjust behavioral response of robot to environmental changes and task requirements. Three different approaches compared that is Random navigation, Rule based navigation and Neuro Evolutionary Navigation, wherein, the neuro evolutionary navigation performed best in complex environment even with limited sensors.

During navigation robot encounters obstacles. Traditional navigation algorithms assume static obstacles, therefore in paper [2] that reviews existing approaches also proposed a new algorithm. Bug algorithm, Potential field methods, Histogram based method, Velocity based methods and Dynamic window approach (DWA) are the existing techniques the paper reviewed. For dynamic obstacle avoidance the authors proposed two algorithms that is Dynamic Window for Dynamic Obstacles (DW4DO) and Dynamic Window for Dynamic Obstacles Tree (DW4DOT). Instead of storing positions the new proposed methods make use of time occupancy grid that includes time and obstacle velocity, allowing the robot to predict future positions of moving obstacles. The new algorithm produces smoother trajectories and avoids dynamic obstacles more safely, while the extended DW4DOT can find better future paths but requires higher computation.

A survey from paper [3] explores the robot navigation strategies designed for human aware navigation in social environments by making the robot to operate safely thereby intersecting robot motion planning and human robot interaction. Human aware navigation frameworks comprises of human motion prediction, pose selection, path planning, behavior planning and local motion control designed for comfort, naturalness and sociability. Therefore, the robot must detect humans in the environment, predict their movements, plan a socially acceptable path and adjust its motion in real time to navigate safely and comfortably around people.

From paper [4], a navigation framework combines Probabilistic Roadmaps (PRM), Rapidly Exploring Random Trees (RRT) and an Elastic Band path optimization algorithm to generate socially acceptable paths. Experiments carried out in real and simulated environments show that the robot can successfully navigate around people and activity spaces while maintaining human comfort.

From paper [5] proposed a person following controller using RGB-D camera and laser range finder to detect and track the human while maintaining a comfortable following distance. This framework incorporates gesture recognition, text-to-speech feedback, leader detection using a Kalman filter and SLAM-based mapping to improve human-robot interaction. Experimental evaluations conducted involves around 80 participants, showed that the robot successfully maintained safe distances with minimal invasion of personal space and low velocity during close interaction.

In paper [6], proposes a multi-sensor autonomous navigation system for agricultural robots that improves localization by filtering unstable vegetation features and detects small obstacles using a PPM-UNet semantic segmentation model. This resulted in more accurate navigation and obstacle avoidance in complex farm environments.

In paper [7], proposes a hybrid navigation system that combines Global Positioning System (GPS) for global guidance and an Adaptive Neuro Fuzzy Inference System (ANFIS). This is applied for autonomous mobile robots to achieve local obstacle avoidance. The main goal is to make a robot to reach a target while avoiding obstacles and choosing a shorter path in cluttered environments.

In paper [8], proposed an Adaptive Cockroach Colony Optimization (ACCO) algorithm for mobile robot path planning. The method improvises the Cockroach Swarm Optimization by using an improved grid map, heuristic search and adaptive rotation strategy suitable for rod like robots. This simulation resulted that ACCO produces shorter collision-free paths and successfully navigates narrow passages, outperforming traditional swarm algorithms such as Ant Colony Optimization. The approach is suitable for autonomous robot navigation in environments rich with obstacles.

In paper [9], integrates Adaptive Deep Reinforcement Learning (ADRL) with a Revised Pine Cone Optimization (RPCO) algorithm. This is done to optimize learning parameters such as learning rate, number of episodes and steps. Environmental information such as velocity, distance to target and sensor readings is read by the robot to generate actions that control its movement. A reward function is also added to guide the robot to reach the target while avoiding obstacles and maintaining safe distances. Approximately 95% success rate in obstacle avoidance with improved path smoothness and efficiency in indoor navigation tasks is resulted in this method.

From paper [10], this paper proposes a cloud based fuzzy inference system called Trust Annotator. This determines robot trust levels using confidence, experience and emotion inputs to get secure and socially aware interactions in cloud robotics.

In paper [11], is a survey of contact based Physical Human Robot Interaction (pHRI). This study is regarding how safely robots interact with humans through direct physical contact. This study reviews recent developments in robot perception, motion planning, control strategies, sensing systems, learning methods and ethical considerations for safe interactions primarily in applications like industrial collaboration, rehabilitation therapy, surgical assistance and object handovers.

In paper [12], a telepresence robot control system transmits human gestures using force sensor data and deep learning. A Nintendo Wii Balance Board is used for capturing human motion. The force distribution and centre of pressure data is collected and then segmented. This is later classified using convolutional neural networks to recognize six gestures such as pointing, nodding and bowing. This system achieved 83.5% segmentation accuracy and 77.8% gesture recognition accuracy., where the recognized gestures are transmitted in real time to a humanoid robot called Pepper.

In paper [13], proposed a navigation framework for autonomous mobile robots integrating laser based environment mapping with an adaptive grid based path planning algorithm. The system dynamically recalculates optimal trajectories based on newly detected obstacles. This resulted navigation accuracy of approximately 2–3 cm in indoor experiments.

In paper [14], develops a low cost omnidirectional telepresence robot using Kalman filter based navigation and WebRTC video streaming. This is done for a reliable remote monitoring and communication with low delay and accurate obstacle avoidance.

In paper [15], presents the design of an IoT enabled telepresence robot for healthcare environments that allows doctors to interact with patients remotely while safely navigating hospital spaces. The robot uses infrared and ultrasonic sensors to detect obstacles. An encoder and magnetometer is used for localization and orientation. This is designed on a microcontroller based control system. The motion of the robot is controlled using Proportional Integral Derivative (PID) based speed, position and orientation controllers, and also along with filtering to reduce sensor noise. The system was tested in a simulated hospital environment where the robot traveled from a doctor's office to a patient ward while avoiding obstacles. Experimental results show that the proposed controller-based approach provides stable navigation, fast response time and fewer collisions. This outperformed the A* algorithm in travel time and distance. The proposed telepresence robot can be cost-effective, reliable and suitable for remote healthcare interaction in situations such as pandemics.

3. Telepresence Robot Systems and Applications

Telepresence robots that are designed to act as physical replacements of remote users, enabling interaction within environments combines mobile platforms, audiovisual communication, sensing and user interfaces to support remote presence. Beyond communication, effective telepresence requires smooth motion, safe navigation and appropriate interaction behaviors, particularly in human environments. This section further understand different telepresence system designs and application.

In paper [16], proposed an immersive telepresence platform that integrates stereo vision, binaural audio and dual motion control also with user head tracking and automatic audio-visual orientation to improve remote interaction and reduce the user's control burden.

In paper [17], a teleoperated mobile robot named Telerobot is proposed. This is designed for in-home healthcare assistance. A usability experiment with rehabilitation professionals conducted showed that telepresence robots can support remote clinical evaluations in home environments. Thus, this demonstrated the importance of advanced teleoperation interfaces. With a robust locomotion mechanisms for safe navigation in cluttered domestic spaces telepresence robot can achieve more applications in hospitals, crowded meetings and industrial applications.

In paper [18], is a study of consumer perceptions of disable employees using robotic assistive technologies. A comparison of telepresence robots through remote operation with a wearable robot used during in-person service showed that employees serving from telepresence robots are observed more negatively due to mechanistic dehumanization. A mechanistic dehumanization is a scenario wherein a human is perceived as more machine like because of increased psychological distance. Therefore, wearable robotic assistance allowed employees to remain physically present, maintaining human interaction and positive evaluations. Therefore, a telepresence robot design with human awareness and improved interaction is needed reducing the mechanistic dehumanization.

In paper [19], examines telepresence robots influence cooperation between students compared to video conferencing. Telepresence robots increased social presence, making participants feel more connected during collaboration in an experiment with 122 students working in pairs. But this leads to robomorphism, wherein interaction partners perceived each other as more machine-like. With a robot design to enhance social presence can improve collaborative learning reducing robomorphism.

In paper [20], is a study of application where telepresence robots support remote students, values in classrooms, focusing on identity, privacy and courtesy. Using a Beam telepresence robots in a field study with 22 university students to examine students remote participation needed practical adjustments such as controlling movement, communication and positioning. This challenged the uncertainty about presence, privacy risks and interaction etiquette. Therefore, a better design to reduce manual teleoperation with obstacle avoidance is needed.

In paper [21], investigates the impact of intercultural seminars using telepresence robots on students called Cultural Intelligence (CQ). This experiment is conducted between universities in Germany and Kenya with 135 students. The research combined lectures, discussions and robot mediated interactions. Active participants using telepresence robots showed significant improvements in metacognitive, cognitive and behavioral CQ compared to a control group. Technical issues in connectivity problems affected usability. Overall, the study demonstrates that telepresence based digital exchanges can effectively enhance intercultural learning and provide a promising alternative to physical student mobility.

In paper [22], to reduce workload on medical staff studies the use of telepresence robots (TPRs) in healthcare to support an ageing population. A test is conducted with 25 participants using a Double 3 robot wherein three simulated scenario that is patient history collection, health measurements and fall assistance for elderly patients is tested. This resulted in enhance remote medical supervision, training and communication. But complete replacement of human healthcare professionals with telepresence robots cannot be entertained due to technical limitations, patient acceptance and ethical concerns.

In paper [23], a qualitative study in Denmark on expectations of telepresence robots among children with cancer, neuromuscular diseases or anxiety that led to significant school absenteeism is done. Interviews of children and their teachers revealed that both groups viewed telepresence robots as valuable tools for maintaining academic learning and social connections with classmates. The robot reduce isolation and help them stay involved in school activities, with flexible learning opportunities.

In paper [24], investigates a mobile telepresence robot improved to support people with mild cognitive impairment (MCI) and Alzheimer's disease living at home. In a semi-structured interviews with patients, caregivers and clinicians, researchers identified key usability and design requirements. Requirements like voice commands, emergency help buttons, medication reminders, and remote video communication in needed.

In paper [25], this project investigates the effectiveness of telepresence robots in reducing loneliness and social isolation among older adults living at home. This non-randomized clinical study, wherein 60 participants aged 65 plus use the Cutii telepresence robot for 12 weeks, followed by a 12-week follow-up. The robot supported communication, remote health consultations and social activities. This study shows the application effectiveness to keep a user engaged in public activities despite the age.

In paper [26], highlighted role of telepresence robots in healthcare systems using the COVID-19 pandemic to minimize direct human interaction. To reduce infection risk telepresence robots is used for patient interaction, medical assistance, cleaning and medicine delivery. Various robot control techniques such as joystick, touchscreen, gesture, eye gaze, glove and brain signal interfaces, evaluating their response times and effectiveness. Challenges like latency, limited autonomy and lack of human-like interaction, emphasizes the need for improved intelligent control and reliable communication.

In paper [27], a review examines the feasibility of telepresence robots for improving social connection in older adults with dementia. Four studies involving three robotic systems is analyzed. The findings indicate that telepresence robots enable real-time video communication between patients and caregivers, promoting emotional engagement and social interaction.

In paper [28], proposed a telepresence framework combining digital twins (DT), extended reality (XR) and collaborative robots for remote collaborative robot programming. This system allows a local operator using mixed reality and a remote operator using virtual reality to alternately program and supervise robot tasks. A real time point cloud streaming and digital twin synchronization improves the workspace for telepresence. Experimental evaluation shows that the approach requires very high bandwidth and low latency, with future 6G communication technologies this technique is highly useful.

In paper [29], proposed a distributed architecture for Ambient Assisted Living (AAL) environments that integrate IoT devices, assistive robots and a virtual caregiver. The system uses delta Conflict free Replicated Data Types (δ -CRDT) to synchronize shared knowledge across multiple software agents, also ensuring consistency with low

communication overhead. A publish subscribe middleware supports efficient data exchange among sensors, robots and cloud components. This is implemented using the CORTEX architecture. The system supports adaptive behaviour and real-time decision-making, by demonstrating through use cases such as fall detection and robotic assistance for elderly users.

In paper [30], a telepresence robotic system integrates augmented reality (AR) to visualize environmental threats detected by autonomous robots. The system uses the Orpheus-X4 robot with calibrated camera to determine its precise position and orientation. By projecting georeferenced hazard information onto the robot's camera view supports operators to see threats such as radiological sources directly within the live video feed. AR visualization improves situational awareness during remote robotic operations in hazardous environments.

In paper [31], a framework is proposed that supports remote surgical education during travel restrictions such as COVID-19. This used an accelerated Delphi process involving 24 international experts to develop standardized guidance for telepresence applications in robotic surgery training. A systematic review of literature and three Delphi rounds, facilitated consensus on infrastructure requirements, communication protocols, training procedures and ethical accountability. The results emphasize reliable networks, structured communication and performance metrics for safe telementoring. This extends telepresence as a scalable method to expand surgical expertise and training worldwide.

In paper [32], reviews the design and analysis of customized robotic mechanisms. This is used to solve various real world engineering problems. Different kinematic mechanisms such as six-leg robots, RP-chain mechanisms, flexure joints, toggle mechanisms and flapping-wing systems is studied. The study is done to highlight kinematic analysis, mathematical modeling and optimization techniques, to help improve robot performance, load capacity and motion efficiency. Advanced tools like CAD, MATLAB and optimization algorithms are emphasized for mechanism design. The review concludes that modifying existing mechanisms using kinematic principles enables more efficient, adaptable and cost-effective robotic systems for diverse applications.

In paper [33], examines telepresence robots effectiveness in social interaction by supporting remote users to interact with people in distant environments. It distinguishes between telepresence that is a feeling present in a remote environment and co-presence that is feeling socially present with another person. Analysis of technological, contextual and individual factors influencing co-presence is done, which includes visual realism, interactivity, haptic feedback and audio-visual quality. It also reviews telepresence robot systems, adaptive user models and design guidelines to improve human-robot interaction and social engagement.

In paper [34], investigated the design and evaluation of telepresence robot user interfaces tailored for older adults. This focuses on usability and privacy concerns. Two interfaces is developed, generic interface and an enhanced interface called InTouch designed specifically for aging users. A mixed method study with 30 older adults showed that the InTouch interface achieved significantly higher usability scores. This resulted in better navigation performance. Features highlighted is obstacle detection, adjustable robot height and room access control to enhance usability, safety and privacy in telepresence systems.

A common trend is the increasing need for partial autonomy. Manual teleoperation alone is insufficient for sustained use, particularly in complex environments. Thus, a modern telepresence systems increasingly integrate navigation assistance, adaptive behaviors and intelligent control to improve usability and safety. These developments motivate further study in navigation, autonomy and human-aware motion planning techniques discussed in the following sections.

4. Navigation and Motion Control in Telepresence Robots

Navigation and motion control in telepresence robot influences safety, usability, and the sense of presence experienced by remote users. Telepresence robots must support continuous human control while operating reliably in dynamic and human populated environments, thus making telepresence robots fundamentally different from classical autonomous navigation problems.

Robot navigation is the ability of a mobile robot to determine its position in an environment and move toward a target location while avoiding obstacles. Control algorithms that regulate speed, direction and trajectory that govern motion control causes the robot to execute these movements. Early telepresence systems relied primarily on direct teleoperation, where users manually controlled robot motion using live video feedback.

This is highly sensitive to communication latency, limited perception and operator workload. Modern telepresence robots increasingly incorporate automatic motion assistance and low level autonomy to improve robustness.

4.1. Omnidirectional and Holonomic Motion Platforms

Omnidirectional and holonomic motion are the platforms commonly used in telepresence robots. This is designed for indoor environments. Holonomic motion allows the robot can move freely in any direction without changing its orientation. Omnidirectional robots use omni-wheels or mecanum wheels to achieve this capability that allow the robot to move forward, backward, sideways or rotate in place. This type of motion provides greater flexibility than the traditional non-holonomic robot that turns before changing direction.

This mobility is particularly useful in environments such as offices, hospitals or classrooms where space may be limited and obstacles are common. While also allowing the remote user to position the robot smoothly during interactions, the ability to move laterally supports the robot navigate narrow corridors and crowded spaces more easily.

In paper [14], developed an omnidirectional telepresence robot equipped with ultrasonic sensors and Kalman filter-based localization to support stable navigation and obstacle avoidance. Additionally in paper [15], designed an IoT-enabled telepresence robot that uses multiple sensors and PID-based motion control to maintain stable movement and safe navigation in healthcare environments. Omnidirectional and holonomic motion platforms improve maneuverability and reduce the effort required from remote operators. This makes telepresence robots easier and safer to control in indoor environments.

4.2 Obstacle Avoidance and Collision Prevention

Obstacle avoidance is a another important requirement for telepresence robots that operate in real environments. Robots are usually controlled by a remote user, the operator depends mainly on video feedback to navigate the robot. Delays in video transmission, limited camera view or hidden obstacles make it difficult for users to react quickly and avoid collisions. Thus an automatic obstacle detection and collision prevention mechanisms is used to improve safety.

Techniques like Bug algorithms, potential field methods, histogram-based approaches, and the Dynamic Window Approach (DWA) suggested in paper [2] allow the robot to detect obstacles and adjust its motion to prevent collisions. Adaptive frameworks that uses laser based mapping and adaptive path planning to update robot trajectories when new obstacles are detected is discussed in paper [13]. Use of ultrasonic and infrared sensors together with control algorithms to detect obstacles and adjust motion in real time improves navigation [14], [15].

Many telepresence robots use reactive collision prevention wherein the robot intervenes only when a potential collision is detected. This approach for dynamic environments maintains user control while ensuring safe operation.

4.3. Sensor Fusion and State Estimation for Navigation

Estimation of the robot's position, orientation and movement when a robot moves in real environments, sensor readings may contain noise or errors due to lighting conditions, uneven surfaces or obstacles. Delays in communication between the robot and the remote operator can affect navigation performance. Solutions like sensor fusion, which combines information from multiple sensors to obtain a more accurate estimate of the robot's state is currently investigated in Telepresence robot systems.

By integrating data from different sensors such as cameras, laser scanners, ultrasonic sensors, encoders and magnetometers, sensor fusion improves localization and motion control. State estimation algorithms process this combined data to determine the robot's position and movement more reliably. In paper [13], proposed a navigation

framework that integrates laser-based environment mapping with adaptive path planning to improve navigation accuracy in indoor environments. In paper [14], implemented a Kalman filter based navigation system in an omnidirectional telepresence robot to improve localization accuracy and motion stability. Additionally in paper [15], designed a telepresence robot that combines infrared and ultrasonic sensors with encoder and magnetometer data to estimate orientation and position while also maintaining stable motion control.

4.4. Shared Control and Motion Assistance

Shared Control and motion assistance is a method where both the robot individually and the remote user is controlling the movement of robot to improve safety and ease of operation in telepresence application. High level commands like direction or target movement is given by user. The robot automatically assists with with low-level tasks like obstacle avoidance, speed adjustment and trajectory correction. This approach is useful in telepresence robots environments where remote users may have limited perception due to camera view, communication delays or network latency. Robot intervene when necessary to prevent collisions or unsafe movements while still maintaining user authority over navigation in a shared autonomy. In paper [5], demonstrate how robots can assist navigation by automatically tracking and maintaining safe distances from users.

4.5. Impact of Communication Latency on Navigation

Communication latency and the quality of video transmission between the robot and the remote user affects the navigation performance of telepresence robots. Real time communication technologies like WebRTC aim to reduce latency and improve remote control responsiveness [14]. Communication delays can cause accidents with obstacles, difficult operation, low quality video and audio causing reduction in accuracy. Delay in communication in healthcare environments affect interaction quality and navigation performance, especially when robots operate in dynamic spaces with people and moving obstacles. Advances in telepresence frameworks that integrate digital twins and extended reality technologies also emphasize the need for high bandwidth and low latency networks to support reliable remote operation [28].

4.6. Discussion

The studies reviewed in this section that highlights important considerations for navigation and motion control in telepresence robots in which robot mobility design plays a major role in usability. Omnidirectional and holonomic platforms increases maneuverability and thus, allows robot to move smoothly in narrow indoor spaces. Reliable sensing and state estimation essential for stable navigation with sensor fusion techniques that combine data from multiple sensors help reduce localization errors and improve motion stability particularly in environments where individual sensors may be affected by noise or environmental conditions. The shared control approaches provide an effective balance between user control and autonomous assistance. Improvements in delays in video transmission or network latency can affect the operator's ability to react to obstacles. Thus this section suggests that effective telepresence robot navigation depends on the combined integration of mobility design, sensing, control strategies and communication infrastructure than just relying on a single navigation algorithm.

5. Mobile Robot Navigation Technologies

Challenges faced by Telepresence autonomous mobile robots includes localization uncertainty, dynamic obstacles and limited perception of the surrounding environment. Telepresence robots operating in complex indoor environments such as offices, hospitals and classrooms, need reliable navigation becomes essential for safe and efficient operation. Improved methods for path planning, obstacle avoidance and adaptive decision making include intelligent navigation approaches such as sensor-based navigation, swarm optimization algorithms, fuzzy logic based control systems and deep reinforcement learning methods. Therefore, understanding these navigation technologies is important for improving telepresence robot performance. The following subsections review navigation approaches developed for mobile robots that can also support adaptive and reliable telepresence robot operation in real world environments for research studies.

5.1. Adaptive Navigation in Dynamic Environments

Adaptive navigation is the ability of a robot to change its movement behavior based on sensor feedback and environmental conditions. The robot continuously adjusts its trajectory according to obstacles, changes in the environment or task requirements instead of following a fixed path. A dynamic environment such as people walking, objects being moved or doors opening and closing wherein a telepresence robots frequently operate in such environments, especially in hospitals, classrooms or offices need smooth movements.

In paper [1], compared three navigation strategies like random navigation, rule-based navigation and neuro-evolutionary navigation. The results showed that learning-based navigation methods can adapt more effectively in complex environments. In paper [6], proposed an adaptive navigation system for robots operating in agricultural environments, where terrain and obstacles frequently change. Their method combines stable feature localization with multi-sensor obstacle detection to help the robot maintain accurate navigation even when environmental conditions vary.

5.2. Human-Aware and Socially Aware Navigation

Human aware navigation considers the presence and movement of people in the environment. Instead of focusing only on reaching a target location and avoiding obstacles, the robot also takes into account human comfort, safety and social behavior. In paper [3], provide a comprehensive survey of human-aware navigation systems, understanding methods robots perform to adjust their speed, direction, and distance when moving near people to ensure comfortable and socially acceptable interactions. In paper [4], proposed a navigation approach that models human density and activity spaces to generate paths that avoid interfering with human movement. By integrating techniques such as probabilistic roadmaps (PRM), rapidly exploring random trees (RRT) and path optimization, the robot can move smoothly while respecting social boundaries.

5.3. Navigation in Unstructured and Partially Known Environments

Unstructured environment refers to spaces where the layout is irregular or constantly changing. Places such as outdoor areas, farms, or cluttered indoor spaces requires navigation strategies to avoid obstacles. In a partially known environment robot does not have a complete map and must rely on sensors to detect obstacles and update its path while moving. Robots must handle issues like sensor noise, uneven surfaces, and unexpected obstacles. In paper [6], developed an adaptive navigation system for agricultural robots that integrates stable feature localization with multi-sensor obstacle detection. This approach filters unstable environmental features and uses semantic segmentation to detect obstacles more accurately, allowing the robot to navigate safely in complex outdoor environments.

5.4. Learning Based and Optimization Techniques

Learning based methods and optimization algorithms that help robots plan safer and more efficient paths are the new navigation methods. This improves robot movement strategies by learning from experience or interaction with the environment. In paper [9], proposed a navigation system that combines adaptive deep reinforcement learning with an optimization technique to improve obstacle avoidance and path planning in indoor environments. In paper [8], introduced an adaptive cockroach colony optimization algorithm, a method to improve path planning by generating shorter collision-free routes and allowing robots to navigate through narrow passages. While optimization algorithms to generate efficient paths the learning based techniques allow robots to adapt to complex and changing environments. Combining these methods with sensor based navigation can improve reliability and help robots operate more effectively in dynamic indoor environments.

5.5. Summary of Key Outcomes

The navigation technologies form the foundation for developing telepresence robots that can operate safely, adapt to environmental changes and support reliable remote interaction in real world environments. Adaptive navigation methods enable robots to modify their movement based on environmental changes and sensor feedback, allowing them to operate effectively in dynamic environments. Human aware and socially aware navigation approaches ensure that robots move safely and comfortably around people. Multi-sensor perception and navigation in

unstructured environments improve the robot's ability to detect obstacles and maintain accurate localization. Learning based and optimization techniques provide advanced methods for path planning and obstacle avoidance. Reinforcement learning approaches allow robots to learn effective navigation strategies from experience, while optimization algorithms generate efficient collision-free paths.

6. Adaptive Autonomy and Artificial Intelligence

To intelligently assist human operators while still maintaining user control, adaptive autonomy ensures telepresence robot continuously balance human commands with automatic decision making for a safe and efficient operation. This is implemented through artificial intelligence (AI) techniques. Based on environmental feedback and previous experience the learning based navigation methods like reinforcement learning support the robot actions. In paper [10], [11] and [12] deep reinforcement learning with optimization, Cloud-based trust modeling approaches and gesture recognition systems are several AI researches done.

6.1. Levels of Autonomy in Telepresence Robots

Levels of autonomy in telepresence robot is differed based on how much control is handled by the human operator and how much is managed by the robot itself. The telepresence robot are designed to maintain human supervision while allowing robot to assist with navigation and safety tasks.

In the lowest level of autonomy, the robot is controlled by the remote user completely. Using video feedback from the robot's camera the operator directly commands movement. This approach preserves full user authority. But this can increase operator workload and may lead to navigation errors when the environment is complex or when network delays occur.

In the intermediate level, telepresence robots use shared autonomy. Here, the robot assists the user by performing low level tasks such as obstacle detection, collision avoidance and speed regulation. User still provides navigation commands, but the robot automatically intervenes when unsafe conditions are detected.

The robot can perform tasks such as path planning, obstacle avoidance and localization automatically in the highest autonomy, while the user provides only high-level instructions. Advances in AI based navigation and adaptive control methods assists robots to handle more complex tasks while still maintaining human oversight when necessary. To balance safety, efficiency and user control shared autonomy is generally considered the most practical approach. Table 1 gives the overall navigation approaches and autonomy levels in telepresence robots.

Table 1. Navigation approaches and autonomy levels in telepresence robots

Navigation / AI Method	Key Idea	Suitable Autonomy Level	Reference
Rule-based/Adaptive Navigation	Robot adjusts motion using sensor feedback and predefined rules	Shared autonomy	[1]
Multi-sensor Adaptive Navigation	Combines multiple sensors for localization and obstacle detection	Semi-autonomous navigation	[6]
Deep Reinforcement Learning	Robot learns navigation strategies through interaction with environment	High autonomy	[9]

Trust-based AI Models	Evaluates reliability and interaction safety in cloud robotics systems	Assisted autonomy	[10]
Gesture-based Telepresence Control	Human gestures used to control robot actions	Human-centered autonomy	[12]

6.2. Reinforcement Learning for Adaptive Navigation

Reinforcement learning (RL) is an artificial intelligence technique wherein robots learn navigation strategies through interaction with their environment. The robot behavior improves by observing the results of its actions. In the learning process, the robot performs an action, evaluates the outcome and gradually learns which actions lead to better navigation performance. Reinforcement learning is commonly used for tasks such as obstacle avoidance, path planning and motion decision making. The robot collects information from sensors such as distance to obstacles, position relative to the target or movement direction and then selects actions like moving forward, turning or adjusting speed. Robot receives positive reward when it successfully moves toward the target while avoiding obstacles.

6.3. Adaptive Neuro Fuzzy Control Models

Adaptive Neuro-Fuzzy Inference Systems (ANFIS) are hybrid artificial intelligence models that combine the learning ability of neural networks with the reasoning capability of fuzzy logic systems. Fuzzy logic is useful for handling uncertain or imprecise information by using linguistic rules. Traditional fuzzy systems require experts to manually design these rules and parameters. Neural networks automatically learn patterns from data but often lack interpretability. Neuro fuzzy systems integrate these two approaches, allowing the robot to learn control rules from data while still maintaining an understandable rule-based structure.

Neuro fuzzy models are often used to control robot movement. This is done by processing sensor inputs such as distance to obstacles, direction to the target and robot velocity. Later the system generates appropriate control outputs such as steering angle or speed adjustment. Because the system can adapt its rules through training, it can improve navigation performance in changing environments.

In paper [7], a hybrid navigation framework combines Global Positioning System (GPS) guidance with an Adaptive Neuro-Fuzzy Inference System (ANFIS) for local obstacle avoidance. The GPS provides global direction toward the target, while the ANFIS controller adjusts the robot's movement to avoid obstacles and maintain safe navigation. This resulted the hybrid system helps the robot reach its destination efficiently while adapting to cluttered environments.

6.4. Optimization Based and Bio-Inspired Algorithms

The methods used in mobile robotics navigation includes path planning which is finding the most efficient route between the robot's current position and the target location while minimizing factors such as travel distance, time or collision risk. Different paths are evaluated based on a cost function, and the robot selects the path with the lowest cost. Bio-inspired algorithms are behaviors observed in nature such as swarm intelligence and collective decision-making. These algorithms simulate how groups of animals or insects explore their environment and find optimal routes and thus explored in navigation problems. Bio-inspired algorithms have become useful tools because of their ability to search large solution spaces and adapt to complex environments..

6.5. Trust Aware and Cognitive Models

In systems that combine human control with autonomous assistance user trust plays an important role in the successful operation of telepresence robots. Robots assist users with tasks such as navigation, obstacle avoidance or decision-making, the operator must trust that the system will behave safely and reliably. If the level of trust is too low, users may avoid using autonomous features where as excessive trust may lead to over-reliance on the system, which can create safety risks.

Therefore, trust-aware models attempt to evaluate and manage the level of trust between the human operator and the robotic system. Factors such as system reliability, past performance and user experience is considered to estimate how much the operator should rely on the robot's autonomous capabilities. In paper [10], a cloud-based trust evaluation framework is proposed that considers parameters such as confidence, experience and emotional responses to determine trust levels in robotic interactions. This approach help improve the reliability and acceptance of robotic systems operating in human centered environments.

6.6. Discussion

A trade-offs between adaptability, transparency and computational complexity is always observed in the models. Reinforcement learning provides adaptability, neuro fuzzy models offer interpretability and shared control ensures user agency. Effective telepresence systems integrates multiple AI techniques within a unified architecture.

7. Human--Robot Interaction and Social Presence

The effectiveness of a Human-robot interaction (HRI) in telepresence robot depends not only on its technical capabilities but also on how naturally people can interact with. Social presence is defined based on the feeling that a remote person is genuinely present in the environment through the robot. This sense of presence requires reliable audio visual communication, smooth robot movement and interaction behaviors which must feel natural to both the remote operator and people nearby. Studies show that the design of telepresence systems should consider factors such as communication quality, interaction comfort, and the robot's physical appearance to support positive user experiences [33].

User acceptance and trust. Is another important aspect of HRI in telepresence robots. When robots operate in shared human environments, people must feel comfortable interacting with them. Therefore, designing interfaces and control mechanisms that are easy to use, particularly for elderly users or individuals with limited technical experience must be noted [34].

7.1. User Perception and Social Acceptance

User perception helps in determining how people accept and interact with telepresence robots. Factors like robot's appearance, movement behavior and communication style can influence how comfortable users feel during interactions. Research on workplace accessibility also suggests that telepresence robots can support inclusion by enabling remote participation while maintaining social interaction [18]. Additionally, human like characteristics can increase engagement and cooperation among users [19]. Moderate levels of anthropomorphism are generally preferred, as overly human like robots may create unrealistic expectations about their capabilities.

7.2. Interaction in Educational and Collaborative Settings

Telepresence robots designs are expected to support active participation and effective communication for remote users. Unlike standard video conferencing tools, telepresence robots allow remote participants to move within the physical environment, observe classroom activities and interact more naturally with teachers and peers. Apart

from the fact robot should help the remote user feel like a visible and active member users expect the robot to provide clear audio visual communication, smooth mobility, and responsive control so that remote participants can engage in discussions, group activities and collaborative tasks [20], [23].

7.3. Physical Interaction and Proximity

Navigation of telepresence robot quickly can cause discomfort or anxiety among nearby users. Therefore, Physical interaction and spatial proximity play an important role. The movement of robot must be smooth and safe. There is a need for safe motion planning, compliant control and reliable sensing systems in a healthcare or assistive environments. This is achieved through good PID control and sensory feedback to measure distance and speed of dynamic obstacles [2], [15].

8. System Architectures, Middleware, and Integration

Telepresence robots combine multiple components such as mobile robot platforms, sensors, communication networks, computing units and user interfaces. The telepresence systems operate as distributed cyber physical systems, wherein hardware and software components work together to enable remote interaction and robot mobility. Telepresence robots must support real time communication, navigation and human interaction. Recent telepresence systems also integrate technologies such as cloud computing, Internet of Things (IoT) and digital twins to support advanced features including remote monitoring, adaptive autonomy and collaborative operation [28], [29]. This section reviews key architectural components and integration approaches used in modern telepresence robot platforms.

8.1. Architectural Paradigms in Telepresence Robots

Internet of Robotics Things (IoRT) is a framework where robots are connected with sensors, cloud services and other devices through networked communication systems. This allows robots to share environmental information, receive updates and coordinate with external systems for improved decision making and monitoring [29]. In concept of cloud robotics where computational tasks such as data processing, learning and decision support are performed in remote cloud servers rather than on the robot itself. This approach supports telepresence robots to access greater computational resources while reducing onboard hardware requirements.

Digital twins which create virtual representations of robots and their environments allow developers and operators to simulate robot behavior, test navigation strategies and monitor system performance remotely [28]. In addition, augmented reality (AR) interfaces can enhance operator awareness by overlaying information about the robot's environment directly onto the user's display, improving remote situational understanding [30].

8.2. System-Level Evaluation Metrics

Telepresence robots operate as integrated cyber physical systems involving hardware, software, communication networks and human interfaces, thus, requires considering both technical performance and user experience. Another important metric is latency, which refers to the delay in communication between the robot and the remote operator. Low latency is essential for responsive control, especially when the user must react quickly to obstacles or environmental changes.

High communication delays can negatively affect navigation accuracy and reduce the quality of interaction. System reliability measures the ability of the telepresence system to operate continuously without failures. Reliable systems ensure stable communication, consistent sensor operation and uninterrupted remote interaction.

Scalability for systems that may support multiple robots or multiple users in large environments such as hospitals or educational institutions. Scalable architectures allow the system to handle increased computational and communication demands. Additionally, Transparent systems is needed improve user trust and make it easier for operators to understand robot behavior.

8.3. Architectural Suitability for Adaptive Telepresence

Capabilities in navigation, communication, sensing and human interaction must be considered for an architecture wherein modern distributed architectures combines onboard robot intelligence with external computational resources and communication networks. Internet of Robotics Things (IoRT) based architectures allow robots to connect with sensors, cloud services and external devices to obtain environmental information and support context aware navigation.

Cloud robotics architectures extend robot capabilities by offloading computationally intensive tasks such as learning algorithms, perception processing and decision-making to remote servers and thus, enables telepresence robots to implement advanced artificial intelligence functions without requiring powerful onboard hardware.

Digital twin architectures create virtual models of the robot and its environment, allowing developers and operators to test navigation strategies, simulate tasks and monitor system behavior in real time. Such architectures are useful for validating autonomous behaviors before deploying them in real environments. Similarly, augmented reality (AR) interfaces improve transparency in telepresence operation by providing visual overlays of environmental information, helping operators better understand robot navigation and surroundings.

8.4. Discussion

A well designed architecture must coordinate several components, including sensing modules, navigation algorithms, communication systems and human interfaces. These components must operate together in real time to ensure smooth navigation, stable communication and effective human–robot interaction.

Modern telepresence robots combine onboard processing with external computational resources such as cloud platforms and networked sensor systems and helpful to run AI algorithms like obstacle avoidance. Approaches such as IoRT frameworks enable context aware data exchange between robots and connected devices.

The cloud robotics architectures support advanced computation for learning and decision-making. However, the integration of these technologies also introduces challenges like communication latency, system reliability and cybersecurity become critical concerns when multiple components operate across distributed networks. Complex architectures may increase system integration effort and cost for deployment.

Therefore, successful telepresence systems must balance advanced capabilities with reliability, transparency, ease of integration and secure protocols. Table 2 summarizes the main architectural layers and their roles in telepresence robot systems.

Table 2. Key architectural layers in telepresence robot systems

System Layer	Main Function	Example Components
Hardware layer	Physical mobility and sensing	Wheels, motors, cameras, LiDAR, ultrasonic sensors
Perception layer	Environment sensing and localization	Sensor fusion, SLAM, obstacle detection

Navigation & control layer	Motion planning and robot control	Path planning, obstacle avoidance, adaptive navigation
Communication layer	Data exchange between robot and operator	Wi-Fi, WebRTC, network protocols
Middleware layer	Coordination between software modules	ROS, IoRT frameworks
AI & autonomy layer	Decision-making and learning	Reinforcement learning, adaptive control
Human interface layer	Remote interaction and control	Teleoperation interface, AR visualization

9. Existing Reviews and Comparative Perspectives

Instead of focusing on a single application domain or technical component in the existing literature, the present review adopts a broader and more integrated perspective. This work connects telepresence robot applications with technologies including mobile robot navigation, adaptive autonomy, artificial intelligence methods and human robot interaction principles. By combining insights from telepresence studies and general mobile robotics research, the review provides a comprehensive system level understanding of how navigation, autonomy, communication and interaction mechanisms collectively influence telepresence robot performance, and this comparative analysis also reveals several opportunities for future research. In particular, many advances in autonomous navigation, adaptive control, and intelligent decision making developed for mobile robots have not yet been fully applied to telepresence systems and thus addressing these gaps may significantly improve the reliability, usability, and autonomy of next-generation telepresence robots.

10. Open Challenges and Research Gaps

Some of the challenges faced by telepresence robot identified as a research gap is listed below :

- 1) Reliable navigation method in dynamic human environments needs to be tested in real-world spaces such as hospitals, offices, and classrooms involve unpredictable human movement and constantly changing layouts.
- 2) Ensuring safe, socially compliant and efficient navigation in dynamic environments.
- 3) Many telepresence robot rely on manual teleoperation and adaptive autonomy has yet to make its way in a dynamic and crowded environment.
- 4) A telepresence system to dynamically adjust autonomy levels based on environmental complexity and user intent require further research.
- 5) Trust based system to improve confidence of user to trust robot operations need new strategies.
- 6) IoRT frameworks and advanced interfaces can introduce latency, security concerns and integration complexity.

In addition, the lack of standardized evaluation metrics makes it difficult to compare different telepresence systems. Addressing these challenges will be essential for developing reliable and widely accepted telepresence robots.

11. Future Research Directions

This section addresses the future of telepresence robots toward adaptive, reliable and socially acceptable systems that requires coordinated progress across navigation, autonomy, interaction and system integration.

11.1. Adaptive and Context-Aware Autonomy

Research in adaptive navigation and learning based robotics shows that robots can improve performance by adjusting their behavior using sensor feedback and environmental information thus improving robot autonomy levels. Context aware autonomy can be achieved by integrating environment perception, user intent recognition, and adaptive control mechanisms. Reinforcement learning based navigation methods allow robots to learn effective obstacle avoidance strategies and adapt to complex indoor environments [9]. Safer navigation in dynamic environments is possible through Adaptive Neuro Fuzzy Inference Systems that can adjust control decisions based on environmental inputs [7].

Performance metrics such as task completion rate, frequency of autonomous intervention, user workload and system recovery after failures needs to be employed. Telepresence robots can achieve more reliable and user-centered operation in real-world environments by combining adaptive navigation algorithms, intelligent decision-making models and scalable system architectures.

11.2. Human-Aware Navigation in Dense Environments

Traditional obstacle avoidance methods focus mainly on collision prevention and to take it further navigation in densely populated environments remains a significant challenge for telepresence robots. Robots should detect nearby people, predict their motion and plan paths that maintain appropriate interpersonal distances and smooth movement patterns [3]. Future research include integrating human intention prediction, social behavior modeling and adaptive motion planning into telepresence navigation systems.

Such integrated system can perform well in dynamic environment. Indicators can be used to evaluate human aware navigation performance are interpersonal distance violations, navigation smoothness, collision frequency and user comfort ratings. Improving these aspects will help telepresence robots operate safely and gain greater acceptance in real-world human-centered environments.

11.3. Long-Term Deployment and Real-World Validation

Currently short-term experiments or controlled laboratory environments limits understanding of how telepresence systems perform during continuous real-world use. For telepresence robots to become widely adopted in environments such as healthcare facilities, schools and workplaces, it is important to evaluate their performance over longer periods of time. Long term deployments allow researchers to study system reliability, maintenance requirements and user interaction with the robot during everyday activities.

11.4. Integrated System Architectures and Standardization

Telepresence robots that incorporate advanced technologies such as cloud computing, IoRT frameworks and digital twin systems becomes increasingly complex. This complexity creates challenges in integrating hardware components, software modules, communication systems, and user interfaces into a single reliable platform. Future telepresence robot systems should adopt modular and standardized architectures so that different components can be developed, upgraded and maintained more easily.

Common middleware frameworks that enable communication and coordination between different subsystems of the robot needs to be integrated. Middleware platforms can support tasks such as data exchange, sensor integration and control coordination so as to integrate navigation algorithms, perception systems and user interfaces within a unified architecture [29]. Emerging technologies such as digital twin frameworks can provide virtual representations of robots and environments, supporting system monitoring and testing before real world deployment [28].

11.5. Ethical, Privacy, and Societal Considerations

Ethical and societal issues must be carefully considered as telepresence robots often operate in sensitive environments such as homes, hospitals and workplaces, where they may collect video, audio and other personal data. To maintain trust in telepresence systems one must ensure data privacy and secure communication protect users. Designing transparent systems that clearly communicate robot actions further improves confidence of user. Ensuring that these technologies remain affordable, accessible and equitable across different communities is crucial. Overall, future research should adopt a holistic approach that combines technical innovation with ethical awareness, human-centered design and system level thinking to ensure responsible and sustainable deployment of telepresence robot technologies.

12. Conclusion

This paper presents review of emerging telepresence robot technologies with a focus on navigation, adaptive autonomy, human–robot interaction and system architecture. The motivation to this study arises due to increasing demand for remote presence technologies in domains such as healthcare, education, workplaces and assistive living. Fundamental navigation techniques and motion control strategies is addressed in this review that support safe robot mobility in dynamic environments. Mobile robot technologies includes adaptive navigation methods, learning-based algorithms and bio-inspired optimization approaches.

Human robot interaction aspects such as social acceptance, user trust and long-term engagement were discussed, emphasizing the importance of human-centered design in telepresence systems. System architectures, middleware frameworks and integration strategies were further reviewed to highlight how distributed computing, IoRT systems and digital twin technologies support scalable telepresence platforms also highlighting the potential latency, scalability and difficulty faced to form a unified architecture for a telepresence application. Future research can focus on developing context-aware autonomy, socially compliant navigation strategies and modular system architectures that enable robust and scalable telepresence deployment. By combining advances in robotics, artificial intelligence and human-centered design, telepresence robots can provide safer, more reliable, and more meaningful remote interaction in real-world environments.

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