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DESIGN AND ARCHITECTURE OF A LOW-COST AI-ENABLED TELEPRESENCE ROBOT FOR REMOTE HEALTHCARE

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ABSTRACT

The growing demand for accessible healthcare services, particularly in resource-limited environments, exposes the limitations of conventional telemedicine systems that rely on stationary video communication [1], [6], [7]. Such approaches restrict a physician's ability to interact dynamically with patients and clinical surroundings, thereby limiting the effectiveness of remote diagnosis and care. This paper presents the design and architecture of a low-cost, AI-enabled telepresence robot intended to enhance remote healthcare delivery through mobility and intelligent assistance [4], [5].

The proposed system integrates a mobile robotic platform with an IoT-based control interface, enabling healthcare professionals to remotely navigate hospital spaces and communicate with patients in real time [1], [8]. An embedded artificial intelligence module is incorporated to support functionalities such as obstacle detection, basic navigation assistance, and human interaction features, thereby improving usability and operational safety [8], [9].

The design emphasizes affordability and scalability by utilizing widely available components, including mobile devices, low-cost microcontrollers, and wireless communication technologies [1], [6]. This makes the system particularly suitable for deployment in rural and under-resourced healthcare settings, where access to continuous medical supervision and specialist consultation is often limited [2], [3].

Although the work is presented at a design level without experimental validation, the feasibility of the proposed architecture is discussed in terms of improving healthcare accessibility, operational efficiency, and remote patient management while maintaining cost-effectiveness [4], [5].

INDEX TERMS: Telepresence Robot, Remote Healthcare, Internet of Things (IoT), Artificial Intelligence (AI), Low-Cost Systems, Telemedicine, Mobile Robotics, Human–Robot Interaction.

I. INTRODUCTION

The increasing demand for accessible and efficient healthcare services has highlighted significant disparities in the availability of medical expertise, particularly in rural and resource-constrained settings [1], [6]. Limited access to specialized doctors and healthcare infrastructure often leads to delayed diagnosis, inadequate treatment, and increased patient risk [3]. In many developing regions, the ratio of medical professionals to patients remains critically low, further intensifying the need for innovative solutions that can bridge the gap between patients and healthcare providers [5].

Telemedicine has emerged as a promising approach to address these challenges by enabling remote consultation through audio and video communication technologies [1], [7]. It allows patients to receive medical advice without the need for physical travel, thereby saving time and reducing healthcare costs [6]. However, conventional telemedicine systems are largely restricted to stationary setups, such as desktop computers or fixed cameras, which limit a doctor's ability to interact dynamically with patients and their surroundings [4]. This lack of mobility reduces situational awareness and restricts the effectiveness of remote diagnosis, particularly in complex clinical environments such as hospital wards, emergency units, and intensive care settings [5].

To overcome these limitations, telepresence robotics has gained attention as an advanced solution that combines real-time communication with physical mobility [4]. Telepresence robots enable doctors to remotely navigate within healthcare environments, observe patients from different angles, and interact more naturally with medical staff [5]. Despite these advantages, many existing telepresence robotic systems are expensive, complex, and often lack intelligent features, making them impractical for large-scale deployment in low-resource settings [4].

In recent years, the integration of artificial intelligence (AI) with robotic systems has opened new possibilities for enhancing autonomy, safety, and interaction capabilities [8], [9]. AI techniques can assist in navigation, obstacle detection, and basic human interaction, thereby improving the overall functionality of telepresence systems [8]. Additionally, the use of Internet of Things (IoT) technologies enables seamless communication between devices, ensuring real-time control and monitoring [1].

Motivated by these advancements, this paper proposes the design and architecture of a low-cost, AI-enabled telepresence robot for remote healthcare applications. The proposed system integrates a mobile robotic platform with an IoT-based communication framework, enabling healthcare professionals to remotely control the robot and interact with patients through live video streaming [1], [4]. Furthermore, basic AI functionalities are incorporated to enhance navigation and interaction, while maintaining system simplicity and affordability [8], [9].

The key contributions of this work are summarized as follows:

1. Design of a cost-effective telepresence robotic system suitable for resource-constrained environments;
2. Integration of AI-based features for assisted navigation and human interaction;
3. Development of a scalable and modular system architecture for improved remote healthcare delivery;
4. Emphasis on practical deployment using readily available and low-cost components.

II. PROPOSED SYSTEM OVERVIEW

The proposed system is designed to enable remote healthcare assistance through a low-cost, AI-enabled telepresence robotic platform [4], [5]. It facilitates real-time interaction between healthcare professionals and patients by integrating mobility, communication, and intelligent assistance within a unified framework [1], [4]. The system is structured into three primary components: the doctor interface, the communication layer, and the telepresence robot unit.

The doctor interface serves as the control point for healthcare professionals and can be implemented as a mobile application or web-based dashboard. Through this interface, the doctor can initiate video communication, send navigation commands, and monitor the robot's status in real time. This ensures ease of use and accessibility across various devices without requiring specialized hardware [6], [7].

The communication layer is responsible for enabling seamless data exchange between the doctor and the robot. It utilizes wireless internet connectivity, typically through Wi-Fi, along with IoT-based communication protocols to ensure reliable transmission of control commands and video data [1]. This layer plays a critical role in maintaining low-latency communication, which is essential for real-time operation [6].

The telepresence robot unit comprises a mobile robotic platform equipped with a microcontroller, motor drivers, a camera system, and a power supply. The robot receives control signals from the doctor via the communication layer and executes movement accordingly [9]. Simultaneously, it captures live video using a mounted mobile device or camera module and streams it back to the doctor [1]. An embedded AI module enhances the system by providing basic functionalities such as obstacle detection and assisted navigation, thereby improving operational safety and usability [8], [9].

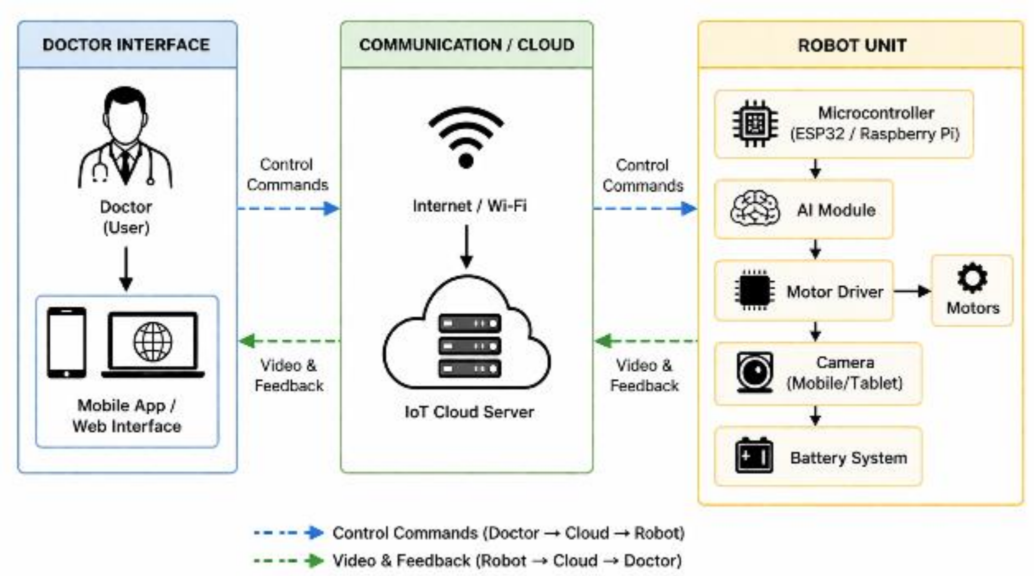

Fig. 1. Overall System Architecture of the Proposed Telepresence Robot.

III. SYSTEM ARCHITECTURE

The system architecture of the proposed telepresence robot is designed to achieve efficient real-time operation while maintaining low cost and scalability. It is divided into three major components: hardware architecture, software architecture, and communication framework. Each component plays a critical role in ensuring seamless interaction between the doctor and the remote environment.

A. Hardware Architecture

The hardware architecture focuses on building a cost-effective and functional robotic platform capable of mobility, communication, and basic sensing **[9]**. The robot is constructed on a four-wheel drive chassis, providing stability and ease of movement across hospital environments such as corridors and patient rooms.

At the core of the system is a microcontroller unit, such as an ESP32 or Raspberry Pi, which is responsible for processing incoming commands and controlling the robot's operations. Motor drivers are interfaced with the microcontroller to regulate the movement of DC motors, enabling directional control including forward, backward, and turning motions [9].

A mobile device or tablet is mounted on the robot to function as a camera unit for live video streaming. This approach significantly reduces system cost by utilizing readily available hardware [6]. The system is powered by a rechargeable battery pack, ensuring portability and uninterrupted operation. Optional sensors, such as ultrasonic sensors, may be included to support obstacle detection and enhance safety [2].

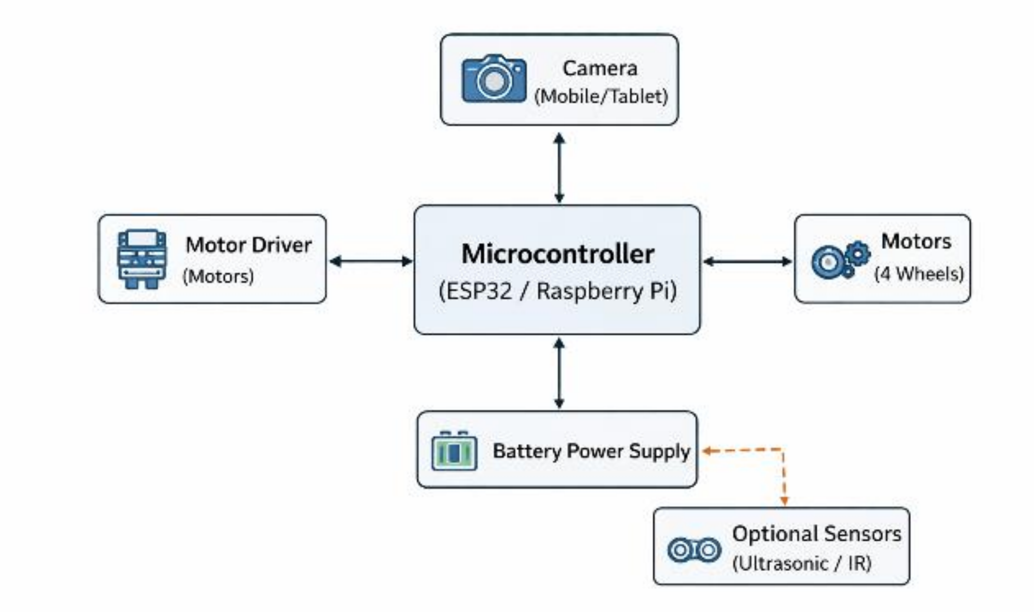

Fig. 2. Hardware Architecture of the Telepresence Robot.

B. Software Architecture

The software architecture is responsible for system control, data processing, and user interaction. It is structured into multiple layers to ensure modularity and efficient operation.

The top layer consists of the user interface, where the doctor interacts with the system via a mobile or web application. This interface allows the user to send control commands and view live video streams [7]. The communication layer handles the transmission of data using IoT protocols such as HTTP or MQTT over a wireless network [1].

The control layer resides within the robot and interprets incoming commands, translating them into appropriate motor actions. Additionally, this layer manages the integration of AI functionalities and system feedback [8]. The execution layer directly interfaces with hardware components, enabling real-time actuation and video streaming.

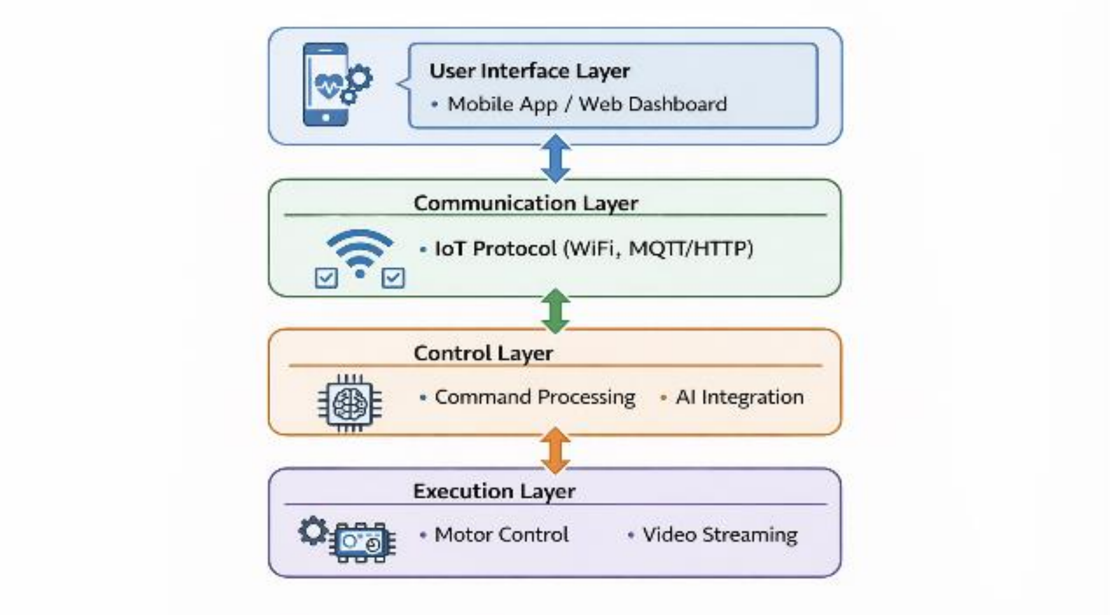

Fig. 3. Software Architecture of the System.

C. Communication Framework

The communication framework enables real-time, bidirectional data transfer between the doctor and the robot. It ensures that control commands are transmitted efficiently while maintaining continuous video feedback [1].

Commands generated from the doctor interface are sent through the internet to the robot's microcontroller via the IoT communication layer. The robot processes these commands and performs the corresponding actions [9]. Simultaneously, live video captured by the camera is streamed back to the doctor, enabling real-time monitoring and interaction [6].

The system is designed to minimize latency and ensure reliable connectivity, which are essential for effective teleoperation [1]. Basic status information, such as battery level and connectivity status, can also be transmitted to enhance system awareness.

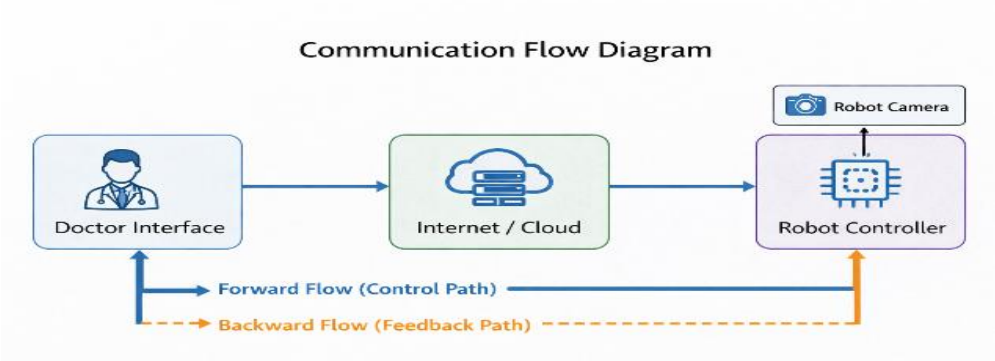

Fig. 4. Communication Flow Diagram.

IV. AI-ENABLED MODULE DESIGN

The integration of artificial intelligence (AI) within the proposed telepresence robot enhances its functionality by enabling assisted navigation, improved interaction, and increased operational safety [8], [9]. Unlike conventional telepresence systems that rely solely on manual control, the proposed design incorporates lightweight AI modules to provide intelligent support while maintaining low computational and cost requirements.

A. Intelligent Navigation and Obstacle Detection

One of the primary challenges in teleoperated robotic systems is safe navigation in dynamic environments [9]. To address this, the proposed system incorporates a basic AI-based obstacle detection mechanism. Visual input from the camera is processed using computer vision techniques to identify obstacles in the robot's path [10].

Simple algorithms based on image processing can be employed to detect edges, shapes, or motion, allowing the system to alert the operator or assist in avoiding collisions [10]. This reduces the cognitive load on the doctor and improves the safety of operation in crowded hospital environments.

B. Human Detection and Interaction

To enhance doctor–patient interaction, the system integrates basic human detection capabilities. Using image-based recognition techniques, the robot can identify the presence of a person within its field of view [10]. This feature can assist the doctor in quickly locating patients and maintaining focus during interaction.

Additionally, this module can be extended to support face detection and basic tracking, allowing the robot to maintain alignment with the patient during communication. Such capabilities contribute to a more natural and effective remote consultation experience.

C. Assisted Control and Decision Support

The AI module also provides assisted control features to complement manual operation. For example, the system can suggest movement adjustments when obstacles are detected or restrict unsafe commands that may lead to collisions [8]. These semi-autonomous features improve usability without removing control from the operator.

Furthermore, basic decision-support mechanisms can be integrated to provide alerts related to environmental conditions or system status, enhancing overall system awareness.

D. Implementation Considerations

To maintain low cost and efficiency, lightweight AI frameworks and libraries can be utilized. Image processing and basic machine learning models can be implemented using platforms such as OpenCV or TensorFlow Lite, which are suitable for embedded systems like

Raspberry Pi **[10], [11]**. The focus is on achieving a balance between performance and computational requirements.

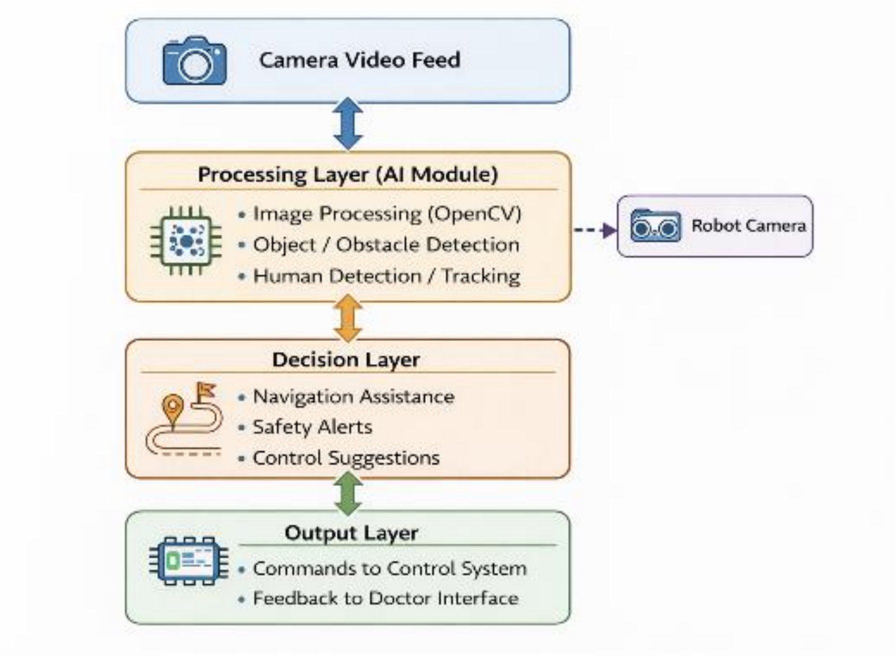

Fig. 5. AI Module Architecture of the Proposed System.

V. SYSTEM WORKFLOW

The system workflow describes the sequential operation of the proposed telepresence robot, illustrating how different components interact to enable real-time remote healthcare assistance [1], [4]. The workflow is designed to ensure simplicity, responsiveness, and effective coordination between the doctor interface and the robotic unit.

Initially, the healthcare professional accesses the system through a mobile or web-based interface and establishes a connection with the robot via the communication network [6], [7]. Once connected, the robot initializes its hardware components, including the camera, motors, and communication modules [9].

After initialization, the doctor sends control commands through the interface to navigate the robot within the healthcare environment. These commands are transmitted via the IoT-based communication layer and received by the robot's microcontroller [1]. The control unit processes the commands and actuates the motors accordingly to achieve the desired movement [9].

Simultaneously, the robot captures live video using the mounted camera device and streams it back to the doctor in real time **[6]**. This continuous feedback enables the doctor to monitor the environment and make informed navigation decisions. The AI module operates in parallel, analyzing the video feed to detect obstacles and assist with safe navigation [8], [10]. If a potential obstacle is identified, the system may provide alerts or assistive corrections. Throughout the operation, system status information such as connectivity and battery level can also be monitored. The process continues until the session is terminated by the doctor, after which the robot returns to an idle state.

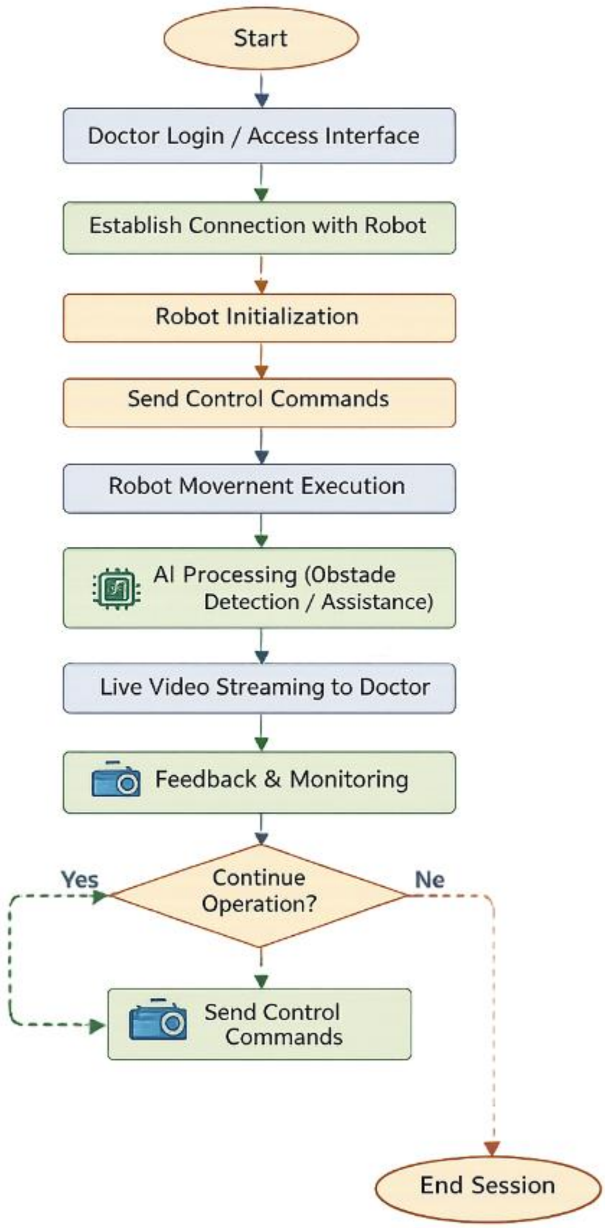

Fig. 6. System Workflow of the Telepresence Robot.

VI. COST ANALYSIS AND SCALABILITY

The proposed telepresence robot is specifically designed to be affordable and scalable, making it suitable for deployment in resource-constrained healthcare environments [1], [6].

Unlike existing commercial telepresence systems, which often involve high-cost proprietary hardware, the proposed design emphasizes the use of readily available and low-cost components without compromising essential functionality [4], [5].

A. Cost Analysis

The overall system cost is minimized by leveraging commonly available consumer electronics and open-source platforms [6]. A significant cost reduction is achieved by using a smartphone or tablet as the primary camera and video communication device, eliminating the need for specialized imaging systems [1]. Similarly, low-cost microcontrollers such as ESP32 or compact computing platforms like Raspberry Pi provide sufficient processing capabilities at a fraction of the cost of industrial-grade controllers [9].

Basic mechanical components, including DC motors, motor drivers, and a standard four-wheel chassis, are inexpensive and widely accessible [9]. Additionally, the use of wireless communication technologies such as Wi-Fi avoids the need for dedicated communication infrastructure [1].

A rough cost distribution of the system includes:

- **Microcontroller and control unit**
- **Motor drivers and motors**
- **Chassis and mechanical assembly**
- **Camera device (smartphone/tablet)**
- **Battery and power management system**

This cost-effective approach makes the system feasible for small clinics, rural hospitals, and temporary healthcare setups [3].

B. Scalability Considerations

Scalability is a key factor in the proposed system design. The architecture allows multiple robots to be deployed across different hospital units or geographic locations, all controlled through a centralized interface [1]. Cloud-based communication enables seamless expansion without significant changes to the core system.

The modular design further supports scalability by allowing additional features, such as advanced sensors or improved AI capabilities, to be integrated as needed [8]. This flexibility ensures that the system can evolve with technological advancements and varying healthcare requirements.

C. Suitability for Resource-Constrained Settings

The proposed system is particularly well-suited for environments with limited infrastructure and financial resources [6]. Its low power consumption, minimal hardware requirements, and reliance on existing internet connectivity make it practical for rural and remote healthcare facilities [1].

By reducing the dependency on physical doctor presence, the system can improve access to medical expertise in underserved areas [3]. It also enables efficient utilization of available healthcare professionals by allowing them to remotely monitor and assist multiple locations [5].

VII. EXPECTED RESULTS AND DISCUSSION

Since the proposed system is presented at a design and architectural level, this section outlines the expected performance, potential benefits, and practical implications of deploying the telepresence robot in real-world healthcare environments.

A. Expected Performance

The system is expected to provide reliable real-time communication between the doctor and the remote environment with minimal latency, depending on network conditions [1], [6]. The mobility of the robot enables dynamic interaction, allowing healthcare professionals to navigate through hospital spaces and observe patients from multiple perspectives [4], [5].

The integration of basic AI functionalities is anticipated to improve operational safety and ease of use. Features such as obstacle detection and assisted navigation can reduce the likelihood of collisions and enhance user confidence during remote operation [8], [9]. Additionally, the continuous video feedback ensures effective monitoring and decision-making [1].

B. Benefits of the Proposed System

The proposed telepresence robot offers several advantages in comparison to traditional telemedicine systems:

- **Enhanced Accessibility:** Enables doctors to reach patients in remote or underserved areas without physical travel [3].
- **Improved Interaction:** Provides a more immersive and flexible interaction compared to fixed video systems [4].
- **Operational Efficiency:** Allows healthcare professionals to manage multiple locations remotely, optimizing time and resources [5].

- **Cost-Effectiveness:** Utilizes low-cost components, making it suitable for large-scale deployment [6].
- **Scalability:** Supports expansion across multiple healthcare facilities with minimal additional infrastructure [1] .

C. Limitations

Despite its advantages, the proposed system has certain limitations:

- **Network Dependency:** Performance is highly dependent on stable internet connectivity [1] .
- **Limited Autonomy:** The system primarily relies on manual control with basic AI assistance [8].
- **Security Concerns:** Data transmission over networks may require robust encryption and security mechanisms [1].
- **Hardware Constraints:** Low-cost components may limit advanced functionalities and precision [9].

D. DISCUSSION

The proposed system demonstrates strong potential in addressing key challenges in remote healthcare delivery, particularly in resource-constrained settings [1], [6]. By combining mobility, real-time communication, and AI-assisted features, the design enhances the capabilities of conventional telemedicine systems [4], [5].

While the absence of experimental validation limits quantitative analysis, the feasibility of the system is supported by the use of existing technologies and well-established communication frameworks [1], [8]. The modular and scalable nature of the design allows for future enhancements, including improved AI capabilities and integration with healthcare data systems [9].

Overall, the system provides a practical and adaptable solution that can contribute to improving healthcare accessibility, especially in regions where medical resources are limited [3].

VIII. FUTURE WORK

The proposed telepresence robot provides a foundational design for remote healthcare assistance; however, several enhancements can be incorporated in future work to improve functionality, autonomy, and real-world applicability.

One important direction is the integration of advanced artificial intelligence techniques to enable higher levels of autonomy [8], [9]. Future systems can incorporate autonomous navigation using simultaneous localization and mapping (SLAM), allowing the robot to move independently within hospital environments without continuous manual control [8]. Additionally, more sophisticated computer vision algorithms can be implemented for improved patient detection, gesture recognition, and activity monitoring [10].

Another area of enhancement involves the integration of healthcare data systems. The robot can be connected to electronic health record (EHR) platforms, enabling doctors to access patient history, reports, and real-time vital parameters during remote consultations [1], [7]. This would significantly improve the quality and efficiency of diagnosis and treatment.

Communication technologies can also be improved by incorporating next-generation networks such as 5G, which offer lower latency and higher reliability. This would enhance real-time control, reduce delays in video streaming, and improve overall system responsiveness, especially in critical medical scenarios [1].

From a hardware perspective, future designs can include additional sensors such as LiDAR, depth cameras, and environmental sensors to improve navigation accuracy and situational awareness [9]. Enhanced power management systems and battery optimization techniques can further increase operational time and reliability.

Security and privacy are also critical considerations for future development. Implementing robust encryption protocols and secure communication frameworks will be essential to protect sensitive patient data and ensure compliance with healthcare regulations [1].

Finally, real-world implementation and experimental validation of the proposed system will be necessary to evaluate performance metrics such as latency, accuracy, reliability, and user satisfaction. Pilot deployments in hospitals and rural healthcare centers can provide valuable insights for further refinement [4], [5].

IX. CONCLUSION

The growing demand for accessible and efficient healthcare services, particularly in resource-constrained environments, calls for innovative technological solutions [1], [6]. This paper presented the design and architecture of a low-cost telepresence robot for remote healthcare, enhanced with intelligent features to improve the capabilities of traditional systems [4], [5]. By integrating IoT-based communication, mobility modules, mapping capabilities, and basic artificial intelligence functionalities, the proposed system enables healthcare professionals to remotely navigate and interact with patients in real time [1], [8].

The architecture prioritizes affordability, scalability, and ease of deployment by utilizing widely available components such as mobile devices, low-cost microcontrollers, and wireless communication technologies [6]. Additionally, the inclusion of AI-assisted features—such as obstacle detection, navigation support, and human detection—enhances the system's usability and safety, making it suitable for practical healthcare applications [8], [9].

Although the system is currently presented at a conceptual and design level without experimental validation, it demonstrates strong potential to improve healthcare accessibility and operational efficiency [3], [5]. Its modular design allows for future enhancements, including the integration of advanced AI techniques, improved communication infrastructure, and compatibility with healthcare data systems [1], [9].

In conclusion, the proposed low-cost, AI-enabled telepresence robot offers a promising solution for expanding remote healthcare services, particularly in underserved regions [3]. It also provides a solid foundation for future research and development in advanced telepresence robotic systems [4].

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