
ROBOT DRIVER DIGITAL AUGMENTED REALITY VIEW

Submitted to the Department of Electrical Engineering,
University of Cape Town, in partial fulfilment of the requirements
for the degree of

BACHELOR OF SCIENCE IN ELECTRICAL AND COMPUTER ENGINEERING

at the

UNIVERSITY OF CAPE TOWN

by

Kudzaishe Kadzimu

Supervised by:

PROF. SIMON WINBERG



ABSTRACT

This MSc project focuses on .. describe the system.

Can provide a few paragraphs, want around 300 - 600 words.

ACKNOWLEDGEMENTS

I would like to gladly express my gratitude to

CONTENTS

Abstract

Acknowledgements	i
Contents	ii
List of Figures	v
List of Tables	vi
List of Abbreviations	vii
Nomenclature	viii
1 Introduction	1
1.1 Background	1
1.2 Problem Description	2
1.3 Objectives	2
1.3.1 Main Objectives	3
1.3.2 Secondary Objectives	3
1.4 Terms of Reference	4
1.5 Scope and Limitations	4
1.6 Plan of Development	5
2 Literature Review	8
2.1 Introduction to Human-Robot Interaction (HRI) and Augmented Reality (AR) .	8
2.1.1 Virtual Reality in Human-Robot Interaction: A Comparison with Augmented Reality	9
2.1.2 Augmented Reality as a Tool in HRI	10
2.2 Mobile Robotics and AR Integration	10
2.2.1 AR as a Communication Tool in Mobile Robotics	11
2.2.2 Multimodal AR Interfaces for Human-Robot Interaction	11

2.2.3	Applications of AR in Mobile Robotics	12
2.2.4	Challenges and Future Directions	12
2.3	Fiducial Marker Systems in HRI	12
2.3.1	Fiducial Marker Systems Overview	13
2.3.2	Choosing the Best Marker System for the Project	14
2.3.3	Visual Interaction in AR-Enhanced HRI	14
2.3.3.1	Applications of Visual Interaction	15
2.3.3.2	Visual Feedback and Real-Time Interaction	15
2.4	AR's Role in Improving User Engagement	16
2.4.1	Enhancing User Engagement through Real-Time Feedback and Visualization	16
2.4.2	Psychological and Practical Benefits	17
2.5	Web-Based Control Interfaces	17
2.5.1	Webserver Framework Options	17
2.5.2	Security and User Experience	18
2.6	Sensor Technologies in Human-Robot Interaction	19
2.6.1	Ultrasonic Sensors	19
2.6.2	Infrared Sensors	20
2.6.3	LiDAR Sensors	21
2.7	Conclusion	22
3	Requirements and Specifications	23
4	Methodology	25
4.1	Overview	25
4.2	Subsystems Overview	26
4.2.1	Camera Module	26
4.2.2	Raspberry Pi	26
4.2.3	Motor Driver and Drive System	27
4.2.4	Web-Based Control Interface	27
4.2.5	Fiducial Marker Detection	28
4.3	Interaction and Dependencies	28
5	Design ad Implementation	29
5.1	System Design	29
5.2	System Architecture	30

6 Results and Discussion	32
6.1 Subsection Name	32
7 Conclusions and Further Work	33
7.1 Conclusions	33
7.2 Recommendations For Further Work	33
A ADC/DAC core	37
A.1 A useful sub appendix	37

LIST OF FIGURES

1.1	Model of autonomous car designed by Leonardo Da Vinci	1
2.1	Overview of the structure of the literature review	8
2.2	Screen Display of work environment with AR additions	9
2.4	Visual comparison of different marker systems	13
2.5	Operation of an Ultrasonic Sensor [1]	19
2.6	LiDAR scanning and mapping process in mobile robotics.	21
4.1	High Level Diagram of how the project will run	25
5.1	Illustration of the hardware layout, showing the arrangement of key components like the Raspberry Pi, motor system, and camera module.	30
7.1	Useful concluding diagram	33

LIST OF TABLES

2.1	Comparison of Fiducial Marker Systems	14
2.2	Comparison of Ultrasonic Sensors	19
2.3	Specifications of the Dagu Infrared Compound Eye	21
2.4	Comparison of RPLIDAR A1 and TF Mini LiDAR (ToF) Sensors	22
3.1	Enhanced Breakdown of sub-tests to be performed in the acceptance testing.	24
5.1	System Architecture Components	31
6.1	Caption for table	32

LIST OF ABBREVIATIONS

- **ADC** – Analogue to Digital Converter
- **ASIC** – Application-specific Integrated Circuit

NOMENCLATURE

Comment: you do not need to have both nomenclature and abbreviations it tends to be redundant.

- **Analogue to digital Converter (ADC):** an electronic device that converts data from its analogue format to its digital form.
- **Very High Speed Integrated Circuits Hardware Description Language (VHDL):** a hardware description language used in electronic design automation to describe digital and mixed-signal systems such as FPGA.

INTRODUCTION

The use of Augmented Reality (AR) in robotic systems has seen a rise in the last decade. This project aims to develop an AR system for a wheeled robot, which should enhance its functionality and provide an overall better user experience. This project builds upon previous work in robotics and aims to integrate AR technology to improve the human-machine experience.

1.1 BACKGROUND

The concept of autonomous vehicles dates back to Leonardo Da Vinci's 16th-century designs, although practical implementations only emerged in the 1980s [2]. Radio-controlled (RC) cars, introduced earlier by Elettronica [3], evolved from combustion engines to electric motors, expanding their applications across various industries [4].



Figure 1.1: Model of autonomous car designed by Leonardo Da Vinci

As we approach the Fifth Industrial Revolution (5IR), the focus shifts to a symbiotic relationship between humans and AI-powered robots, emphasizing workplace efficiency while maintaining a human-centric approach [5]. Augmented Reality (AR) plays a crucial role in this evolution, bridging the gap between humans and machines in areas such as manufacturing, healthcare, and human-robot interaction (HRI) [6].

In the context of autonomous systems, fiducial markers (e.g., ARToolKit, AprilTags, ArUco) have become integral to robotics and AR applications. These markers facilitate robot navigation, environmental mapping, and interaction zone definition. The choice of marker system

depends on specific application requirements, available computational resources, and desired accuracy.

The integration of AR and fiducial markers in robotics enhances perception, navigation, and interaction capabilities, pushing the boundaries of human-robot collaboration and making autonomous robots more adaptable and intelligent.

1.2 PROBLEM DESCRIPTION

As robots continue to evolve with so does our demand for more intuitive and seamless interaction with these robots. Traditional control methods often fall short when it comes to offering the flexibility and situational awareness needed to integrate robots effectively into dynamic, real-world environments. This project addresses several key challenges in the domain of mobile robot control and environmental interaction:

1. **Limited Contextual Awareness:** Current remote-controlled robots often operate with minimal understanding of their surroundings, leading to inefficient navigation and potential safety hazards in complex environments.
2. **Inflexible Control Mechanisms:** Many existing robot control systems rely on fixed command sets that do not adapt to changing environmental conditions or task requirements, limiting their versatility and usability.
3. **Lack of Intuitive Feedback:** Users often struggle to interpret the robot's status, intentions, or responses to environmental stimuli, creating a communication gap between the human operator and the robotic system.
4. **Absence of Dynamic Task Assignment:** Most mobile robots are pre-programmed for specific tasks and lack the ability to receive and interpret new instructions or environmental cues on the fly.
5. **Integration Challenges:** Incorporating augmented reality (AR) elements into robotic systems presents technical challenges in terms of real-time processing, accurate marker detection, and seamless information overlay.

1.3 OBJECTIVES

The primary objective of this project is to enhance human-robot interaction (HRI) by integrating Augmented Reality (AR) technology with mobile robotics. Leveraging AR and visual markers

like ArUco codes, the robot will be able to navigate and perform tasks in a more interactive, intuitive, and human-centered manner, thus improving the overall user experience. This project focuses on providing the human operator with an augmented view of the environment and enhancing the robot's context-awareness to better perform dynamic, real-time tasks.

More specifically, the project seeks to develop a control system that facilitates dynamic, visual-based communication between a human user and the robot. By augmenting the environment with visual markers and AR interfaces, the robot will better understand its surroundings and perform context-aware tasks. Different "control zones" will trigger specific robot behaviors based on the visual markers detected by its camera, providing real-time feedback through AR-enhanced visualizations.

1.3.1 Main Objectives

1. **Development of Control Zones:** AR-based control zones will guide the robot's behavior. These zones will define parameters such as speed adjustments, task initiation, and areas where the robot must stop or change direction based on AR markers.
2. **Integration of Dynamic Instructions:** Using ArUco markers, the robot will receive real-time commands to perform various tasks, including navigation, task execution, and environment-specific instructions triggered by marker detection.
3. **Environmental Mapping and Task Interaction:** The robot will use visual markers to create a simple map of its surroundings, enabling it to track landmarks, avoid obstacles, and interact with specific objects in its environment.
4. **Improving User Engagement:** AR technology will allow users to visually instruct and monitor the robot's progress in real-time, offering a more interactive and immersive user experience that enhances both usability and functionality.

1.3.2 Secondary Objectives

In addition to the main objectives, the project will explore two secondary automated functionalities to improve robot autonomy:

1. **Object Avoidance:** The robot will recognize specific markers (e.g., a warning cone) and avoid coming within a defined distance (e.g., 20cm) of those objects. This feature will prevent the robot from advancing if it is too close to an obstacle, even if the human operator continues pressing forward.

2. **Wheel Slip Detection:** The robot will detect terrain changes that could cause wheel slip, such as transitioning from solid ground to a slippery surface. Instead of relying on wheel rotation counters, the robot will monitor power draw characteristics to detect traction issues and adjust accordingly.

These enhancements aim to address the current limitations in HRI by making robot control more intuitive and responsive in dynamic environments. They also contribute to the broader goal of improving human-robot collaboration in both industrial and everyday contexts, creating a seamless and human-centered interaction model.

1.4 TERMS OF REFERENCE

This project aims to enhance human-robot interaction (HRI) by integrating Augmented Reality (AR) into a mobile robot. The system requirements, established through research, discussions with the supervisor, and analysis of the intended user environment, guide both the technical implementation and user experience. Key requirements include operating in AR-defined control zones, integrating dynamic instructions based on ArUco marker detection, environmental mapping using visual markers, providing real-time visual feedback, implementing object avoidance functionality, and detecting wheel slip events.

To meet these requirements, the system will implement several functionalities, including AR-based control zones, real-time ArUco marker processing, visual marker-based environmental mapping and obstacle avoidance, AR-based visual feedback for operators, object avoidance behavior, and wheel slip detection. Testing procedures have been outlined to ensure the system meets these requirements and functionalities, with specific sub-tests designed to check each function and requirement individually.

1.5 SCOPE AND LIMITATIONS

This project was conducted under several significant constraints that shaped the scope of the research and development process. These constraints were primarily due to limitations in time, budget, and available resources, which directly impacted the scale of the implementation and the range of features that could be developed.

The project had a total budget of R2000, which restricted the procurement of high-end components and forced the use of readily available, cost-effective hardware. Additionally, the project timeline was set at three months, limiting the ability to explore more advanced functionalities

and requiring a focused approach to key objectives. These constraints influenced both the design and testing phases of the project.

Furthermore, ethical considerations were taken into account, particularly in ensuring that no invasive or harmful testing methods were used. The project did not involve human or animal subjects, which helped to avoid potential ethical conflicts and the need for additional approvals.

- **Time constraints:** The project had a strict timeline of three months, which limited the scope of research, prototyping, and testing phases. This required prioritizing key functionalities over more exploratory objectives.
- **Budget limitations:** With a budget of R2000, cost-effective hardware and software solutions had to be utilized, which influenced decisions on components such as sensors, markers, and AR technology. High-end equipment was not feasible.
- **Technical scope:** The project focused on AR integration for basic control and task interaction but did not include advanced machine learning algorithms or high-level autonomy features due to time and resource constraints.
- **Ethical limitations:** The project did not involve any human or animal subjects, thereby avoiding potential ethical conflicts. All testing was performed in controlled environments using non-invasive methods.
- **Environmental considerations:** The robot was tested in a limited set of predefined environments due to time and budget constraints. Broader testing in varying environments or larger spaces was outside the scope of this project.

Despite these limitations, the project successfully demonstrated the integration of AR in human-robot interaction. While the constraints limited the full realization of more advanced features, the focused approach allowed the core objectives to be met within the available resources and timeline. Further development could build upon this foundation to explore more complex functionalities and broader applications.

1.6 PLAN OF DEVELOPMENT

This thesis is structured into six chapters, each focusing on different aspects of the research and development process. The chapters build upon each other to present a coherent narrative from the conceptual framework to the implementation, testing, and conclusions of the project.

Chapter 2: Literature Review

Chapter 2 discusses the foundational technologies, theories, and techniques that underpin this project. It provides an overview of the state of the art in human-robot interaction (HRI), mobile robotics, and the use of Augmented Reality (AR) in robotics. This chapter will also review key research papers and methodologies that are relevant to the design and implementation of AR-enhanced control systems.

Chapter 3: Methodology

Chapter 3 presents the research methodology used for this project. It provides detailed explanations of the procedures, experimental setups, and tools used for the development and testing of the system. In particular, the acceptance tests will be discussed, outlining how each item of functionality and requirement will be meticulously validated through controlled tests. The methodology will emphasize how these tests demonstrate the satisfaction of both functional and system requirements.

Chapter 4: Prototype Design

Chapter 4 focuses on the design of the system. It provides details on the hardware and software design choices, discussing how the various subsystems (e.g., AR integration, control zones, and dynamic instructions) were conceived and implemented. For a prototype-based approach, this chapter will also describe the physical setup, robot design, and any relevant architectural decisions. Visuals such as diagrams, screenshots, and code snippets will be used to illustrate key design elements.

Chapter 5: Results and Analysis

Chapter 5 presents the results obtained from the system tests. These results will showcase how the robot interacted with AR markers and control zones, as well as its performance in dynamic environments. Data from the acceptance tests will be analyzed to assess the system's functionality and its success in meeting the project's objectives. This chapter will also include observations on the system's performance, its limitations, and any issues encountered during testing.

Chapter 6: Discussion and Conclusion

Chapter 6 concludes the thesis by reflecting on the overall project, summarizing the key findings, and discussing the implications of the results. It will cover the challenges faced during the project, how they were addressed, and potential areas for improvement. This chapter will also discuss future work, proposing possible enhancements and directions for further research to extend the project's scope and applications.

References

Finally, all cited works, including books, journal articles, conference papers, and other relevant sources, will be compiled in the References section according to the appropriate referencing style.

LITERATURE REVIEW

This literature review provides a comprehensive exploration of the integration of Augmented Reality (AR) with mobile robotics, focusing on its applications in Human-Robot Interaction (HRI). The review is structured to cover several key areas that are crucial to the development of an AR framework for a 4WD robotic car. Here's an overview of what readers can expect to find in this literature review:

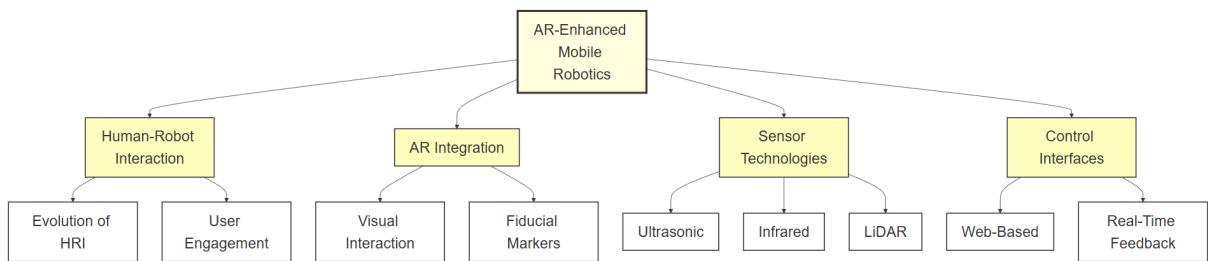


Figure 2.1: Overview of the structure of the literature review

2.1 INTRODUCTION TO HUMAN-ROBOT INTERACTION (HRI) AND AUGMENTED REALITY (AR)

Human-Robot Interaction (HRI) has seen substantial growth in both research and industrial applications, particularly with the advent of collaborative robots (cobots) that work alongside humans in dynamic environments. These robots, unlike their predecessors, are designed to safely interact with humans in shared workspaces, marking a significant shift in industrial automation.

According to [7], HRI evolved from isolated robot systems in manufacturing to collaborative systems where robots assist humans in complex tasks. This shift is largely due to advancements in sensing, control, and human-machine interface technologies that allow robots to perceive their environment and interact intelligently.

Augmented Reality (AR) has emerged as a powerful tool in enhancing HRI by providing a more intuitive and efficient way for humans to interact with robots. AR serves as a bridge that



Figure 2.2: Screen Display of work environment with AR additions

overlays digital information onto the physical environment, enabling users to better understand the robot’s actions and the task at hand [8].

2.1.1 Virtual Reality in Human-Robot Interaction: A Comparison with Augmented Reality

Virtual Reality (VR) and Augmented Reality (AR) have both played significant roles in advancing Human-Robot Interaction (HRI). However, their applications and interaction paradigms differ significantly. Understanding these differences is essential when analyzing how each technology enhances the interaction between humans and robots.

VR offers a fully immersive experience where users interact with robots in a completely simulated world. This makes it particularly effective for applications such as robotic training, simulation, and remote teleoperation. For instance, VR is widely used for training operators and robots in new tasks in a risk-free virtual environment [9]. By immersing the user in a fully virtual environment, VR allows for complex robot interactions, including simulated task execution and environment navigation, which is especially useful in fields such as disaster response, industrial automation, and surgical simulations [10].

AR, on the other hand, overlays digital information onto the real world, making it more suitable for real-time, operational tasks involving physical robots. AR enables users to view critical information such as navigational data, sensor outputs, or planned robot trajectories without losing connection to their real-world environment [11]. This makes AR ideal for applications where humans and robots share the same workspace, such as collaborative manufacturing, logistics,

and maintenance tasks.

While both technologies are beneficial, this literature review will primarily focus on Augmented Reality due to its practical applications in human-robot collaboration.

2.1.2 Augmented Reality as a Tool in HRI

AR enhances communication between humans and robots by offering real-time visualizations and feedback, thus improving situational awareness and reducing errors in task execution. Suzuki et al. [8] propose a taxonomy of AR-enhanced HRI, highlighting the key areas where AR plays a role, such as task guidance, real-time interaction, and environment mapping. In particular, AR's ability to provide visual feedback significantly enhances the user experience by making robot operations more transparent and reducing cognitive load.

Moreover, AR facilitates dynamic task interaction by enabling users to provide real-time instructions to the robot. This is particularly beneficial in industrial applications where task conditions change frequently. AR not only improves task accuracy but also contributes to a more efficient workflow, as robots can quickly adjust their behavior based on user commands and visual markers such as ArUco codes [8].

AR's applications in HRI span various industries, from manufacturing to healthcare. In manufacturing, AR has been utilized to guide robot operations through real-time visual overlays, improving precision and safety in tasks that require close human-robot collaboration [7]. Similarly, in healthcare, AR assists medical robots in performing delicate procedures by providing real-time feedback and guidance, enhancing both safety and operational efficiency [8].

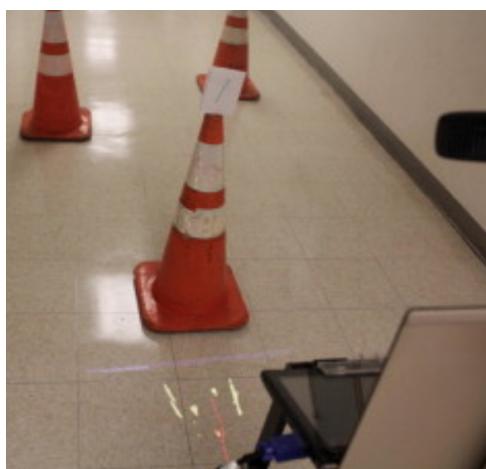
2.2 MOBILE ROBOTICS AND AR INTEGRATION

The integration of Augmented Reality (AR) in mobile robotics has transformed how robots communicate their intentions and interact with their environment. AR not only enhances human-robot collaboration but also provides an intuitive interface for users to understand robot behavior in dynamic and complex environments. Several key studies have explored the use of AR to improve robot navigation, task execution, and real-time interaction between humans and robots.

2.2.1 AR as a Communication Tool in Mobile Robotics

One of the primary challenges in human-robot interaction is communicating the robot's intended actions to human operators. Spatial Augmented Reality (SAR) has proven to be an effective method for achieving this. In the study by Green et al. [12], SAR is used to project information about the robot's intended movement directly onto the physical environment. This method allows users to better anticipate and respond to the robot's actions, reducing uncertainty and enhancing collaboration. Michalos et al. [13] demonstrated the application of AR in industrial settings, where visual feedback aids in task coordination between humans and robots, leading to improved task accuracy and faster response times.

Additionally, Covert et al. [14] explored how spatial AR techniques can improve communication between robots and humans. In their experiment, a robot used visual projections of arrows and simplified maps on the floor to indicate its short-, mid-, and long-term movement intentions. The study found that participants were able to predict the robot's movements with high confidence when the robot projected its intended path. This is especially useful in environments where humans and robots share a workspace, such as hospitals, museums, and factories.



(a) Robot estimating its intended movement. [14].



(b) Robot estimating its intended movement using AR arrows [14].

2.2.2 Multimodal AR Interfaces for Human-Robot Interaction

In addition to visual feedback, multimodal interfaces that combine AR with other modalities, such as voice or gesture recognition, have further improved human-robot interaction. Green et al. [12] developed a multimodal AR interface for mobile robots, allowing users to interact with the robot through visual overlays, voice commands, and gesture-based inputs. This interface improved the efficiency and accuracy of task execution in collaborative environments. The study demonstrated that multimodal AR interfaces allow for more flexible and adaptive human-

robot communication, making the interaction process more intuitive and reducing cognitive load on the user.

2.2.3 Applications of AR in Mobile Robotics

AR's integration into mobile robotics is particularly useful in environments that require constant adaptation, such as manufacturing or logistics. Michalos et al. [13] applied AR in human-robot cooperation in industrial settings, where robots must adapt to rapidly changing conditions. AR provided real-time feedback to users, helping them coordinate with robots for tasks such as assembly or quality control. Moreover, AR visualizations helped robots better navigate dynamic environments, improving both safety and efficiency.

Furthermore, AR's ability to create real-time visual overlays in the robot's workspace has significant implications for task planning and execution. In particular, SAR-based interfaces allow users to visually instruct robots by marking control zones or highlighting obstacles, which the robot then interprets for navigation and task completion [14].

2.2.4 Challenges and Future Directions

While AR's role in mobile robotics has demonstrated significant potential, challenges remain in real-time processing, accurate object recognition, and user feedback latency. As Michalos et al. [13] noted, the integration of AR into robotic systems requires further advancements in sensor technology and computational power to ensure real-time responsiveness in dynamic environments. Future research will likely focus on improving AR's scalability in complex settings, refining multimodal interfaces, and enhancing the autonomy of mobile robots to handle more sophisticated tasks.

2.3 FIDUCIAL MARKER SYSTEMS IN HRI

Augmented Reality (AR) is increasingly used in robotics to facilitate various types of Human-Robot Interactions (HRI). While multiple interaction modalities have been discussed, the remainder of this literature review will focus specifically on visual and marker-based interactions. Below is a list of the different types of interactions possible with AR:

- **Visual Interaction:** AR overlays visual cues such as control zones, instructions, and real-time status feedback, enhancing human comprehension of the robot's operational environment.

- **Gesture-Based Interaction:** Human gestures can be interpreted by robots through AR-enhanced vision systems, reducing reliance on manual interfaces.
- **Speech and Command Interaction:** AR, combined with voice recognition, allows users to issue commands to robots with visual aids providing additional context.
- **Fiducial Marker-Based Interaction:** Fiducial markers such as ArUco or AprilTags provide robots with a way to interpret their environment, helping with localization, navigation, and object detection.

2.3.1 Fiducial Marker Systems Overview

In AR-enhanced HRI, fiducial marker systems are essential for real-time contextual interactions. These systems use visually distinct markers that robots detect through cameras. The most commonly used marker systems include ARToolKit, AprilTags, and ArUco markers, each with unique characteristics suited to various applications.



Figure 2.4: Visual comparison of different marker systems

ARToolKit is one of the earliest fiducial marker systems developed for augmented reality applications. It was widely adopted in early AR systems due to its simplicity and moderate computational requirements. In HRI, ARToolKit has been used in early experiments involving robot navigation and control. However, its robustness is limited compared to more modern systems, and it struggles under challenging lighting conditions [8].

AprilTags are an improvement over ARToolKit, offering significantly higher robustness and detection accuracy. As [15] highlights, AprilTags are designed to provide accurate detection even in adverse environments with variable lighting and occlusion. AprilTags have been extensively used in industrial applications where precise localization is critical, such as warehouse automation and autonomous guided vehicles (AGVs). The system is computationally heavier than ARToolKit but provides superior reliability, making it suitable for applications that demand accuracy over speed [16].

ArUco markers are designed with computational efficiency in mind, offering high detection speed without sacrificing much in terms of accuracy. This makes them ideal for real-time applications, particularly in mobile robotics where swift responses are critical. [17] notes that ArUco markers have been used in various applications including navigation and task execution in dynamic environments such as warehouses. Their simplicity and widespread software support make them a popular choice for developers working on real-time robotic systems.

Table 2.1: Comparison of Fiducial Marker Systems

Marker System	Robustness	Detection Accuracy	Computational Efficiency	Applications
ARToolKit	Moderate	Good	Moderate	Early AR applications
AprilTags	High	Excellent	Moderate-High	Robotics
ArUco Markers	High	Good	High	Real-time robot navigation

2.3.2 Choosing the Best Marker System for the Project

Given the requirements of the project, which involve real-time processing, dynamic navigation, and user interaction, ArUco markers are the most suitable choice. As [16] demonstrates, ArUco markers provide a good balance between computational efficiency and detection accuracy, making them ideal for mobile robotic systems that require fast decision-making. Additionally, the ease of integration with commonly used robotics software such as ROS (Robot Operating System) further justifies their selection for this project.

2.3.3 Visual Interaction in AR-Enhanced HRI

Visual interaction is one of the most common and effective forms of interaction in Augmented Reality (AR)-enhanced Human-Robot Interaction (HRI). It enables users to interact with robots by visualizing contextual information directly within their physical environment. This can include task instructions, control zones, and real-time feedback on the robot's status and performance.

In AR-enhanced visual interaction, the robot's actions and intentions are augmented with overlays that help the human user make informed decisions during interaction. [8] provides a comprehensive overview of how visual interaction enhances HRI by improving situational awareness and reducing the complexity of controlling robotic systems. This is especially useful in industrial applications, where workers interact with robots to execute precise tasks, such as assembly and quality control.

2.3.3.1 Applications of Visual Interaction

Visual interaction in AR has broad applicability across various fields, with significant benefits in improving task accuracy, communication, and overall efficiency. Some notable applications include:

- **Manufacturing and Assembly:** In industries such as automotive and aerospace, visual interaction is used to overlay task instructions on the assembly line, helping workers follow complex procedures. This reduces human error and increases productivity by providing step-by-step visual guidance [15].
- **Healthcare:** In robotic surgery and rehabilitation, visual interaction allows surgeons and therapists to see real-time data overlaid on patients, enhancing precision and safety. AR enhances the accuracy of procedures by showing virtual boundaries and guidelines, ensuring that robots move correctly within the workspace [17].
- **Warehouse and Logistics:** In logistics and warehouse management, AR systems provide real-time visual cues to workers handling robotic systems for item sorting, picking, and delivery. [17] explores the use of AR to improve warehouse efficiency by overlaying instructions on specific zones, helping workers interact more intuitively with robotic arms and autonomous guided vehicles (AGVs).

2.3.3.2 Visual Feedback and Real-Time Interaction

One of the most significant advantages of AR-enhanced visual interaction is the provision of real-time feedback, which facilitates more intuitive robot control. [16] investigates the real-time testing of vision-based systems in AGVs using ArUco markers and AR visualizations. Their research highlights how visual feedback improves decision-making in dynamic environments, helping robots navigate autonomously with greater efficiency.

Visual feedback can take various forms:

- **Control Zones:** Specific areas within the robot's environment are highlighted using AR, guiding the robot's actions and helping the user visualize where the robot can move or interact with objects.
- **Status Updates:** Information such as battery levels, current tasks, or environmental hazards can be projected onto the robot's workspace, allowing users to quickly assess and adjust the robot's behavior as needed.

- **Error Detection:** AR systems can visually highlight potential errors in the robot's movements, such as collisions, off-course navigation or wheel slipping, enabling quick corrective actions.

Suzuki et al. [8] emphasizes that visual interaction not only enhances HRI but also promotes collaboration between human operators and robots by reducing cognitive load. By providing real-time visual cues, AR improves situational awareness and makes controlling robots more intuitive, particularly in environments where precision is critical.

However, there are certain limitations. [15] discusses the challenges of accurately overlaying visual data in real-time, particularly in environments with inconsistent lighting, reflections, or occlusions. Additionally, the processing demands of rendering real-time visualizations may limit the performance of systems with constrained computational resources.

2.4 AR'S ROLE IN IMPROVING USER ENGAGEMENT

Augmented Reality (AR) has significantly enhanced user engagement with robotic systems, particularly in Automated Guided Vehicles (AGVs). By providing intuitive visual feedback and real-time streaming data, AR improves both the psychological and practical interaction between humans and AGVs. The combination of augmented reality and robotics has been a topic of significant research interest, as AR makes robots more intuitive to control and increases user trust in automated systems.

2.4.1 Enhancing User Engagement through Real-Time Feedback and Visualization

One of the key strengths of AR is its ability to provide real-time feedback and visualizations, allowing users to intuitively understand the robot's actions and status. AR-infused streaming technology improves human-robot collaboration by projecting real-time data, control zones, and navigation paths onto the robot's environment [18]. This continuous stream of real-time data reduces cognitive load, enabling users to anticipate and control AGV movements more effectively in dynamic environments. Such real-time visualization allows users to engage more deeply with robotic systems, increasing their confidence in controlling AGVs.

In particular, [18] explore how AR is utilized across different robotic applications, including medical, industrial, and social robotics. For AGVs, they highlight AR's capability to enhance human-robot collaboration by improving real-time task allocation and decision-making pro-

cesses. The visual feedback offered by AR systems reduces the need for constant manual adjustments, thereby increasing operator efficiency [18].

In industrial scenarios, [19] emphasize the role of AR in improving user engagement through its intuitive interfaces. They note that AR helps operators visualize tasks more clearly, thus reducing the learning curve for new users while providing advanced feedback for experienced operators. This is important in environments where quick decisions are necessary [19].

2.4.2 Psychological and Practical Benefits

The psychological impact of AR on user engagement is considerable. Real-time visualizations, such as path projections or task instructions, create a more predictable and transparent interaction between humans and robots. Users become more confident when they can clearly see an AGV's next move, which reduces uncertainty about the robot's behavior and enhances user trust. This **increased predictability** improves user satisfaction and promotes wider adoption of AR-enabled robotic systems [14].

AR also offers practical benefits in rehabilitation settings, where users can engage with robotic systems in therapy. As Makhataeva [19] points out, AR interfaces allow users to interact with AGVs or rehabilitation robots in a natural way, improving patient recovery outcomes. The immersive nature of AR encourages patient involvement, which is crucial in therapeutic contexts [19].

2.5 WEB-BASED CONTROL INTERFACES

Having a functional robot is all well and good but if the robot has an unpleasant or inefficient interface then it ruins the whole user experience. This section will detail different methods of implementing web-based control interfaces, focusing on real-time communication, user interaction, and video streaming.

2.5.1 Webserver Framework Options

Flask is a lightweight Python web framework known for its simplicity and flexibility[20]. It is particularly well-suited for the rapid development of web-based control interfaces. Flask is easy to set up and use, making it ideal for prototyping and small to medium-sized applications. It integrates well with Python libraries commonly used in robotics. However, for real-time features, additional libraries may be required, and its performance can be a concern for large-

scale applications.

Node.js is a JavaScript runtime built on Chrome’s V8 engine, recognized for its event-driven, non-blocking I/O model. Its asynchronous nature makes it highly suitable for real-time applications [21]. Node.js also benefits from a large ecosystem of packages and libraries and is capable of efficiently handling many simultaneous connections. However, it may require more setup compared to Flask, and its callback-based programming can be complex for beginners.

WebSocket integration is essential for real-time control and data streaming, providing low-latency, bidirectional communication over a single TCP connection [22]. This is particularly advantageous when sending control commands and receiving video streams. WebSockets can be integrated with both Flask and Node.js, though careful implementation is required to handle issues such as connection drops and reconnections, and additional security measures may be necessary.

Apache and Nginx are traditional web servers that are robust, highly scalable, and performant, making them popular choices in production environments. They offer extensive documentation and strong security features. However, they may be more complex to set up and configure, and can be overkill for smaller projects or embedded systems like Raspberry Pi [23]. They are typically used in conjunction with application servers rather than for standalone dynamic content.

Flask or Node.js, combined with WebSocket integration, would likely be the most suitable choices due to their ease of use and real-time capabilities. For this project Flask will be implemented due to its ease of understanding for a beginner.

2.5.2 Security and User Experience

While security is a crucial aspect of any robotic system, especially those controlled through web-based interfaces, it’s important to note that for the scope of my project, I’ve chosen not to delve deeply into privacy and security concerns. This decision allows me to focus more intensively on the core functionality and user experience aspects of the system.

In a real-world application, however, it would be critical to implement robust security measures. These would typically include encryption protocols like TLS (Transport Layer Security) to protect the integrity and confidentiality of data exchanged between the robot and the user interface. Additionally, strong authentication mechanisms would be necessary to prevent unauthorized access to the robot’s controls.

2.6 SENSOR TECHNOLOGIES IN HUMAN-ROBOT INTERACTION

When discussing the AR technology, it's difficult to do so without making mention of sensors, sensors allow machines to interact with their environments. Sensors are to machines what eyes and ears are to humans. This section serves as a review for the applicable sensors relevant to this project which is designing a AR framework for a 4WD robotic car.

2.6.1 Ultrasonic Sensors

Ultrasonic sensors are a common choice in mobile robotics due to their effectiveness in obstacle avoidance and distance measurement. These sensors emit ultrasonic waves and measure the time it takes for the waves to reflect back from an object, allowing the robot to calculate the distance from obstacles [24]. This capability provides spatial awareness that is critical for safe navigation. Below is a basic diagram showcasing the operation of an HC-SR04 Infrared Sensor.

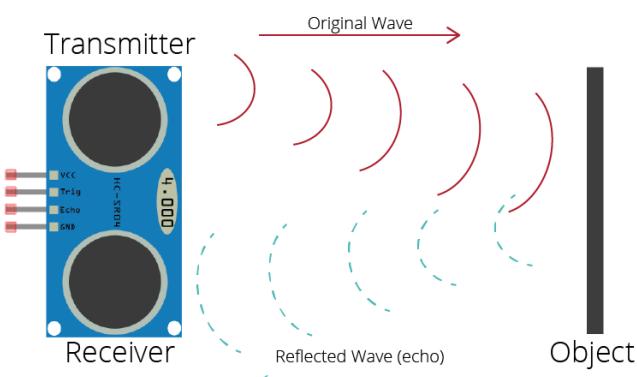


Figure 2.5: Operation of an Ultrasonic Sensor [1]

Below is a comparison of some common ultrasonic sensors used in mobile robotics.

Table 2.2: Comparison of Ultrasonic Sensors

Model	Range (cm)	Operating Voltage (V)	Accuracy	Field of View	Size (mm)
HC-SR04	2-400	5	± 0.3 cm	15 degrees	45 x 20 x 15
Maxbotix MB1000	20-645	2.5-5.5	$\pm 1\%$	42 degrees	22 x 20 x 16
Parallax PING)))	3-300	5	± 0.5 cm	20 degrees	22 x 46 x 16

Ultrasonic sensors are advantageous because of their simplicity, affordability, and ease of integration. For this project, they could provide an excellent mechanism for detecting nearby

obstacles, which is essential for navigation in dynamic environments. Some key properties of ultrasonic sensors include:

- **Wide Range of Detection:** As seen in the table, ultrasonic sensors like the HC-SR04 and Maxbotix MB1000 can detect objects at distances ranging from a few centimeters to several meters. This is beneficial for both short-range and long-range obstacle avoidance.
- **Accuracy and Precision:** Depending on the model, ultrasonic sensors offer good accuracy for distance measurements. For example, the Maxbotix MB1000 boasts an accuracy of $\pm 1\%$, helping ensure that the robot reacts promptly and effectively to its surroundings.
- **Field of View (FoV):** The field of view differs between sensors, affecting the robot's perception. A larger FoV allows the robot to detect obstacles from a wider angle, but may result in less precise focus on individual objects.

Integrating ultrasonic sensors with augmented reality (AR) offers the possibility of visualizing sensor data in real time. For example, AR can highlight areas where the robot detects obstacles, providing the operator with enhanced spatial awareness, preventing collisions, and improving task efficiency. Additionally, real-time data streaming through a visual interface allows for immediate adjustments to the robot's behavior based on sensor readings.

2.6.2 Infrared Sensors

Infrared (IR) sensors are commonly used in mobile robotics for tasks such as proximity detection, line-following, and object avoidance. These sensors emit infrared light and detect the reflection from nearby objects, making them effective for short-range detection in controlled environments [25].

While standard IR sensors, such as the basic proximity IR sensors, serve well in obstacle avoidance and object detection, they have limitations in terms of range, field of view, and accuracy. These standard sensors perform well in specific lighting conditions but struggle in environments with significant ambient light interference [26].

The **Dagu Infrared Compound Eye** shares basic functionality with standard IR sensors but offers significant enhancements. Unlike single-point IR sensors, the Dagu sensor features a compound array of multiple infrared detectors, allowing for a much wider field of view and multi-directional sensing. This enables the robot to detect objects from multiple angles, enhancing spatial awareness and enabling more complex navigation and object tracking tasks [26].

Integrating the **Dagu Infrared Compound Eye** into this project would extend the robot's capabilities by improving its obstacle detection, particularly in dynamic and complex environments. The sensor's wide field of view, combined with real-time AR feedback, could provide users with a more intuitive control system and greater situational awareness, thereby improving human-robot interaction (HRI). Moreover, the sensor could aid in tasks requiring precise spatial awareness, such as navigating around obstacles or detecting specific objects [25].

Table 2.3: Specifications of the Dagu Infrared Compound Eye

Specification	Value
Number of Detectors	4 infrared sensors
Detection Range	200mm
Operating Voltage	5V
Power Consumption	10 mA

Additionally, this sensor could provide valuable data that could be visualized for the user through augmented reality (AR), enabling a more interactive and user-friendly experience.

2.6.3 LiDAR Sensors

LiDAR (Light Detection and Ranging) is an essential technology for mobile robotics that uses laser light to measure distances and create 3D maps of environments. By utilizing LiDAR sensors, mobile robots can detect obstacles, map their surroundings, and navigate autonomously [27].

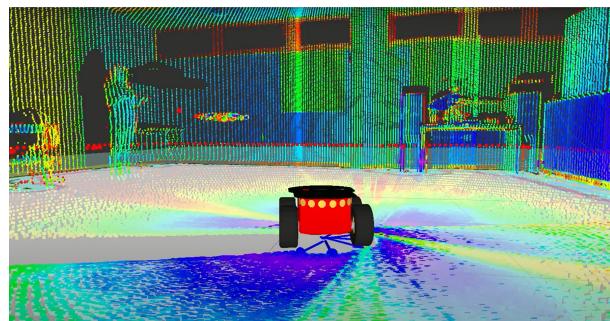


Figure 2.6: LiDAR scanning and mapping process in mobile robotics.

For this review, two LiDAR sensors will be considered although they will not be considered for the project itself: **RPLIDAR A1** and **TF Mini LiDAR (ToF) Laser Range Sensor V2.0**. These sensors offer capabilities that can significantly enhance the robot's ability to perceive and interact with its environment. Below is a comparison of their specifications [27]:

The **RPLIDAR A1** is a 360-degree scanning LiDAR sensor capable of creating a comprehensive map of the robot's surroundings in real time. This would enable the robot to detect objects

and obstacles from all directions, making it ideal for use in complex environments where autonomous navigation is crucial.

Table 2.4: Comparison of RPLIDAR A1 and TF Mini LiDAR (ToF) Sensors

Specification	RPLIDAR A1	TF Mini LiDAR (ToF)
Max Range	12m	12m
Resolution	0.2cm	1cm
Field of View	360° (horizontal)	3.6° (horizontal)
Sample Rate	8000 samples/sec	1000 samples/sec
Power Consumption	5V, 500mA	5V, 140mA
Interface	UART, USB	UART
Size (mm)	97.5 x 60 x 38	42 x 15 x 16

On the other hand, the **TF Mini LiDAR (ToF)** sensor, although more limited in its field of view, offers a compact and lightweight design, making it suitable for applications requiring focused, high-speed distance measurement. Its small size and low power consumption could be beneficial for tasks where precise distance measurements are needed without adding significant weight or power demands.

Both sensors would improve the robot's environmental mapping and obstacle detection capabilities. Visualizing the LiDAR data in an AR interface would provide real-time feedback to users, enabling them to monitor the robot's surroundings and make informed decisions about its movement.

2.7 CONCLUSION

This literature review has explored the integration of Augmented Reality (AR) with mobile robotics, focusing on Human-Robot Interaction (HRI). Key areas such as fiducial marker systems like ArUco markers, sensor technologies, and web-based control interfaces were examined to assess their role in improving real-time visualization and user interaction with robots.

AR has emerged as a crucial tool in enhancing HRI, offering real-time feedback, improved situational awareness, and better task performance. Additionally, sensors such as ultrasonic and LiDAR, combined with AR, hold promise for optimizing navigation and obstacle avoidance in mobile robots.

While AR shows significant potential for advancing HRI, challenges such as real-time processing limitations and the need for secure web-based interfaces remain. These insights will guide the development of my AR framework for the 4WD robotic car, focusing on real-time visualization, intuitive control, and efficient sensor integration.

REQUIREMENTS AND SPECIFICATIONS

This project builds on the primary objective of enhancing human-robot interaction (HRI) by integrating Augmented Reality (AR) into a mobile robot. As outlined in Section 1.3, the system needs to meet specific requirements to ensure it performs as intended. These requirements were established through research, discussions with supervisor, and analysis of the intended user environment. The requirements are designed to guide both the technical implementation and the user experience, ensuring the robot operates seamlessly with AR-based control systems.

- **R1.** The robot must operate in different control zones, defined by AR markers, and adjust its behavior accordingly (e.g., slowing down, stopping, or performing a task).
- **R2.** The system must integrate dynamic instructions based on ArUco marker detection, allowing for real-time task updates.
- **R3.** The AR interface must provide real-time visual feedback for the human operator to improve task monitoring and control.
- **R4.** The robot must include object avoidance functionality, ensuring it maintains a safe distance from recognized obstacles (e.g., warning cones) based on AR markers.
- **R5.** The system should detect and respond to wheel slip events caused by changes in surface traction, providing stability during operation.

To meet these requirements, the system will implement the following functionalities:

- **F1.** Implementation of AR-based control zones that dynamically adjust robot speed, direction, or initiate tasks based on detected markers (R1).
- **F2.** Real-time processing of ArUco markers to update task instructions and provide context-specific navigation and task execution (R2).

- **F3.** AR-based visual feedback will provide the human operator with real-time monitoring of the robot's actions and environmental interactions (R4).
- **F4.** Integration of object avoidance behavior, ensuring the robot maintains a safe distance from obstacles based on AR marker detection (R5).
- **F5.** Implementation of wheel slip detection functionality that monitors the robot's power draw to identify surface traction changes (R6).

Testing will be performed to ensure that the system meets the outlined requirements and functionalities. The table below shows the breakdown of the sub-tests to be performed, with each test linked to the specific functions and requirements it checks.

Table 3.1: Enhanced Breakdown of sub-tests to be performed in the acceptance testing.

Test	Description	Expected Outcome	Functions Checked	Requirements Tested
T1	Test the robot's behavior in AR-based control zones	The robot adjusts speed or direction based on AR markers within defined zones (e.g., slow zone, stop zone).	F1	R1
T2	Test real-time ArUco marker detection for dynamic instructions	Robot recognizes ArUco markers in real-time and triggers corresponding task instructions (e.g., task initiation or environmental change response).	F2	R2
T3	Test AR-based visual feedback for real-time monitoring	The user receives accurate and real-time AR feedback on the robot's position, detected markers, and current task.	F3	R3
T4	Test object avoidance system using visual markers	The robot successfully avoids predefined obstacles marked by ArUco codes within 20 cm, halting or rerouting its path.	F4	R4
T5	Test wheel slip detection and response functionality	The robot detects slip on different surfaces (e.g., sand or wet surfaces) and compensates by adjusting motor power or stopping.	F5	R5

METHODOLOGY

This chapter details the design and implementation of a mobile robotic system using augmented reality (AR), fiducial markers, and remote monitoring to improve human-robot interaction (HRI). It builds on existing research in computer vision-based navigation, AR for HRI, and internet-controlled mobile robots. Design decisions are justified with related literature and practical system requirements.

4.1 OVERVIEW

The high-level diagram illustrates the mobile robot project's architecture, showcasing key components: Raspberry Pi (central processor), camera module, motor control system, fiducial markers, and web-based control interface. The data flow begins with the camera capturing video, which the Raspberry Pi processes for marker detection and navigation. Simultaneously, the web interface sends commands to the Raspberry Pi, which also streams video back to the user.

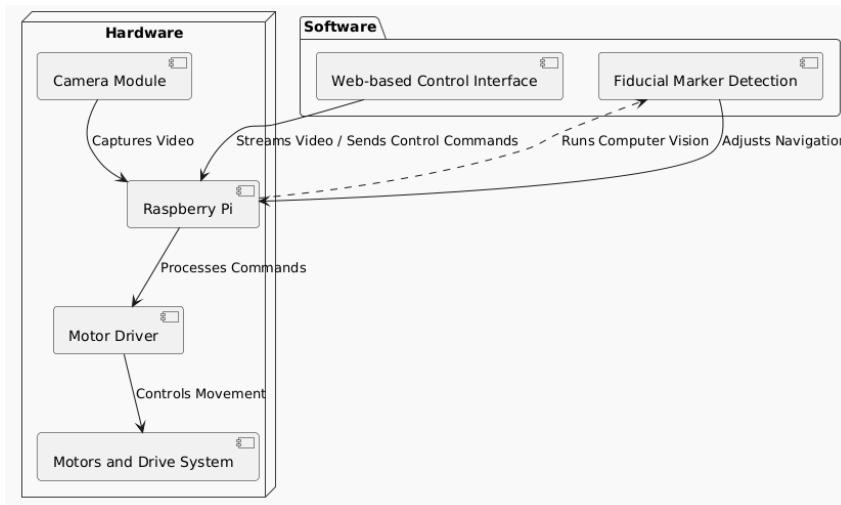


Figure 4.1: High Level Diagram of how the project will run

The methodology centers on the development of a mobile robot system capable of navigation, interaction, and real-time feedback, using AR markers and remote control via a Raspberry Pi

board. Inspired by the works of La Delfa et al. [28], Jacobsen et al. [29], and Vanitha et al. [30], this project seeks to incorporate advances in fiducial marker systems and AR interfaces to improve the efficiency and user engagement in controlling mobile robots.

4.2 SUBSYSTEMS OVERVIEW

This section delves into the various subsystems that form the mobile robot project, discussing their functions, components, and how they contribute to the overall project architecture.

4.2.1 Camera Module

The camera module is responsible for capturing real-time video, which is then sent to the Raspberry Pi for processing. The camera is positioned in such a way that it can capture the environment around the robot, ensuring that fiducial markers and obstacles are visible. This visual data is crucial for navigation and interaction as it enables the system to detect AR markers.

Key Features:

- High-definition video capture
- Low-latency video transmission
- Integration with Raspberry Pi for real-time processing

Role in the System: The camera's primary role is to feed the Raspberry Pi with visual data, which is analyzed to detect fiducial markers for navigation and user interaction. It also serves as the robot's eyes, giving it the ability to avoid obstacles and make real-time adjustments based on the video stream.

4.2.2 Raspberry Pi

The Raspberry Pi acts as the central processing unit (CPU) for the project. It takes input from both the camera module and the web interface, and it performs real-time processing to control the robot's movement, detect fiducial markers, and respond to user commands.

Key Features:

- Centralized control and processing

- Runs image processing algorithms (e.g., OpenCV for fiducial markers)
- Communicates with the web-based control interface for real-time video streaming and command processing

Role in the System: The Raspberry Pi processes the video stream from the camera module, detecting fiducial markers for navigation and control. It also acts as the bridge between the hardware components and the software interface, sending commands to the motor driver and receiving instructions from the web-based interface.

4.2.3 Motor Driver and Drive System

The motor driver is responsible for controlling the movement of the robot by regulating the motors connected to the wheels. The Raspberry Pi sends commands to the motor driver, which in turn adjusts the speed and direction of the motors based on the input received.

Key Features:

- Pulse-width modulation (PWM) control of motor speed
- Direct control over motor direction (forward/reverse)
- Real-time response to commands from the Raspberry Pi

Role in the System: The motor driver takes processed commands from the Raspberry Pi and translates them into physical movement, enabling the robot to navigate the environment. The drive system ensures smooth movement, whether for navigating to fiducial markers or avoiding obstacles.

4.2.4 Web-Based Control Interface

The web-based control interface allows the user to remotely interact with the robot. It streams real-time video from the camera module, enabling the user to see what the robot sees. The interface also allows the user to send commands to the Raspberry Pi, controlling the robot's movements and receiving visual feedback in return.

Key Features:

- Real-time video streaming via web interface

- Command input for remote robot control
- AR marker-based navigation

Role in the System: This interface is the primary method of user interaction. By streaming live video and accepting control inputs, it gives the user complete control over the robot's navigation and tasks.

4.2.5 Fiducial Marker Detection

Fiducial markers play a central role in navigation and interaction in this project. These markers, when detected by the camera, trigger predefined actions or provide the robot with navigation points. The fiducial marker detection is implemented using the ArUco marker system via OpenCV, which is processed by the Raspberry Pi.

Key Features:

- Detection of fiducial markers for navigation and interaction
- Real-time processing for dynamic task execution
- Accurate localization based on marker position

Role in the System: Fiducial marker detection provides spatial awareness to the robot, enabling it to navigate autonomously or follow user-defined paths. By identifying markers, the robot can adjust its movements in real-time, such as avoiding obstacles or performing tasks in specific areas.

4.3 INTERACTION AND DEPENDENCIES

Each subsystem interacts closely to form a cohesive mobile robot system. The camera module captures the visual data, which the Raspberry Pi processes for fiducial marker detection and navigation. The Raspberry Pi also receives commands from the web-based control interface, which then adjusts the motor driver's settings to move the robot. The fiducial marker detection plays a key role in dynamic navigation, providing real-time feedback to the user through the web interface.

DESIGN AND IMPLEMENTATION

This chapter outlines the design and implementation phases of the mobile robot system project. The purpose of this chapter is to describe the system's architecture, the design of each subsystem, the integration of hardware and software, and how these components work together to achieve the goals of this project. The design emphasizes ease of navigation, real-time feedback, and effective control via an intuitive interface.

5.1 SYSTEM DESIGN

The design of the mobile robot system was based on the specific project requirements outlined in Chapter 3. Following a detailed review of relevant literature and an analysis of system needs, the robot's overall design was established. The architecture integrates several key components—Raspberry Pi, camera module, fiducial markers, motor control system, and wireless communication modules—to ensure optimal system performance.

The core decision-making process involved selecting the appropriate technologies and components. Based on the findings from previous research (e.g., Jacobsen et al. [29], La Delfa et al. [28], and Vanitha et al. [30]), which explored various mobile robot control methods using augmented reality (AR) and computer vision, it became clear that a Raspberry Pi-based system with a web interface would provide the required flexibility and ease of control for this project.

After evaluating several options for actuation and navigation, it was determined that motorized control through a motor driver and a four-wheel drive system would provide the most reliable and efficient solution for movement. This decision was supported by studies that demonstrate the performance of motor-driven robots in both laboratory and dynamic environments. Additionally, the use of fiducial markers, such as ArUco or AprilTag markers, was identified as a robust solution for localization and obstacle avoidance (La Delfa et al. [28]; Vanitha et al. [30]).

The integration of these components into a cohesive design was a critical aspect of the project. The Raspberry Pi was chosen as the central processing unit because of its ability to handle computer vision tasks and interface with the hardware seamlessly. The camera module was

selected to provide real-time video streaming, which not only serves as an input for the robot's environment perception but also allows for remote monitoring through the web interface.

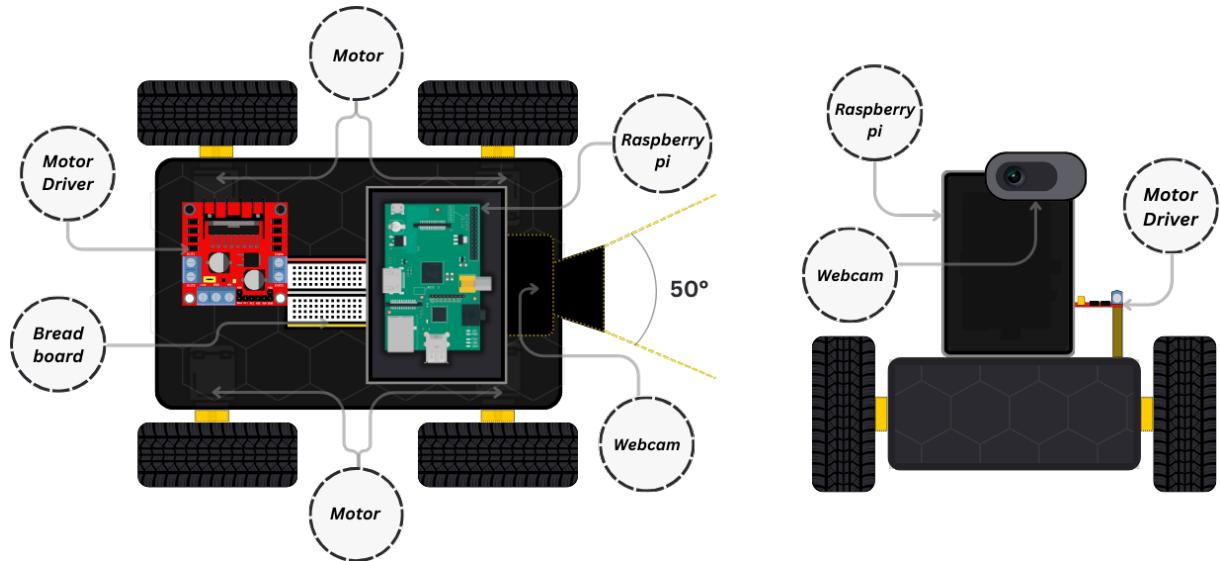


Figure 5.1: Illustration of the hardware layout, showing the arrangement of key components like the Raspberry Pi, motor system, and camera module.

5.2 SYSTEM ARCHITECTURE

The project is composed of several key components, below is a high level overview of all the components that are needed in order execute the project properly.

Table 5.1: System Architecture Components

Component	Description
Microcontroller/Processor	Manages computer vision algorithms and interfaces with hardware. Responsible for overall system control and data processing.
Web Camera	Provides real-time video feed for remote monitoring and vision tasks. Captures high-quality images for processing.
Motor and Drive System	Four-wheel drive system for robot mobility. Includes motors and a motor controller for precise movement control.
Fiducial Markers	Visual markers (e.g., ArUco or AprilTag) placed in the environment to assist with localization and navigation.
Web-based Control Interface	Allows remote control of the robot's movements and camera functions, with video streaming capabilities.
Power Supply	Provides electrical power to all components of the system. Needs to support extended operation and peak power demands.
Chassis	Physical structure of the robot that houses and protects all components. Designed for durability and optimal component placement.
Sensors	Additional sensors for environmental awareness (e.g., ultrasonic sensors, IMU, GPS).
Communication Module	Enables wireless communication between the robot and the control interface, supporting long-range and reliable data transmission.

RESULTS AND DISCUSSION

This chapter describes the tests that were carried out in order to test the system to see that it works according to specified user requirements in section. The system under test was designed in Chapter 5.

6.1 SUBSECTION NAME

This section describes some results. This is how you can reference an appendix Appendix A.1 as you might want to offload stuff to the appendix.

Here is an example table

Table 6.1: Caption for table

Parameter	Value
Lower cutoff frequency	100 kHz
Mid frequency	200 kHz
Higher cutoff frequency	300 kHz

CONCLUSIONS AND FURTHER WORK

This chapter presents the conclusions and future work for this dissertation.

7.1 CONCLUSIONS

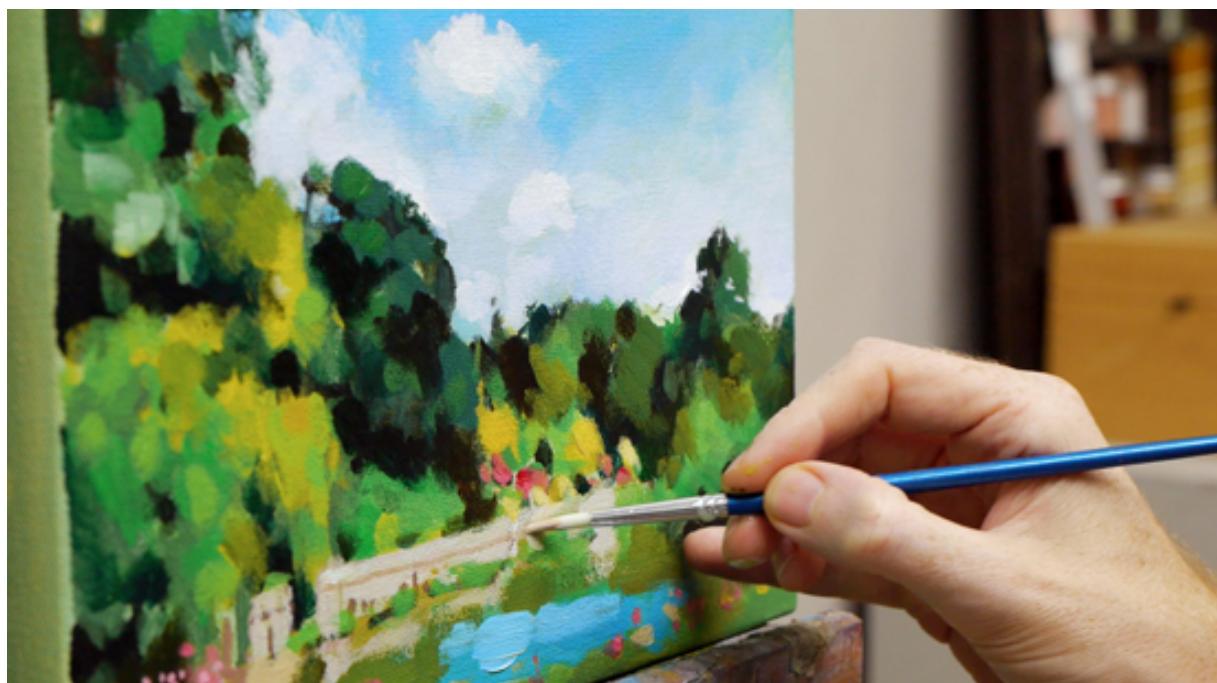


Figure 7.1: Useful concluding diagram

7.2 RECOMMENDATIONS FOR FURTHER WORK

BIBLIOGRAPHY

- [1] Random Nerd Tutorials. Complete guide for ultrasonic sensor hc-sr04 with arduino. <https://randomnerdtutorials.com/complete-guide-for-ultrasonic-sensor-hc-sr04/>, 2021. Accessed: 2024-09-21.
- [2] Mobileye. A brief history of autonomous vehicles – from renaissance to reality. *Mobileye Blog*, 2023. Accessed: 2024-08-18.
- [3] RC Crush. A complete rc car history. *RC Crush*, Apr 2023. Accessed: 2024-08-18.
- [4] "Gregor Klancar", "Andrej Zdesar", "Saso Blazic", and "Igor Skrjanc". *Wheeled Mobile Robotics*. Google Books, 2017. Accessed: 2024-08-18.
- [5] S. Samuels. What is the fifth industrial revolution and are we in it? *Skills Portal*, 2023. Accessed: 2024-09-12.
- [6] M. Dalle Mura and G. Dini. Augmented reality in assembly systems: State of the art and future perspectives. In Svetan Ratchev, editor, *Smart Technologies for Precision Assembly*, pages 3–22, Cham, 2021. Springer International Publishing.
- [7] A. Hentout, M. Aouache, A. Maoudj, and I. Akli. Human–robot interaction in industrial collaborative robotics: a literature review of the decade 2008–2017. *Advanced Robotics*, 33(15–16):764–799, 2019. Accessed: 2024-09-16.
- [8] R. Suzuki, A. Karim, T. Xia, H. Hedayati, and N. Marquardt. Augmented reality and robotics: A survey and taxonomy for ar-enhanced human-robot interaction and robotic interfaces. *arXiv preprint arXiv:2203.03254*, 2022. Accessed: 2024-09-16.
- [9] E. Coronado, S. Itadera, and I. G. Ramirez-Alpizar. Integrating virtual, mixed, and augmented reality to human-robot interaction applications using game engines: A brief review of accessible software tools and frameworks. *Applied Sciences*, 13(3):1292, 2023.
- [10] Yu Lei, Zhi Su, and Chao Cheng. Virtual reality in human-robot interaction: Challenges and benefits. *AIMS Robotics*, 7(4):477–495, 2022.

- [11] Michael Walker, Thao Phung, Tathagata Chakraborti, Tom Williams, and Daniel Szafir. Virtual, augmented, and mixed reality for human-robot interaction: A survey and virtual design element taxonomy. *arXiv preprint*, 2019.
- [12] S. A. Green, X. Chen, and M. Billinghurst. Collaborating with a mobile robot: An augmented reality multimodal interface. *Robotics and Autonomous Systems*, 122:103–110, 2019. Accessed: 2024-09-16.
- [13] G. Michalos et al. Augmented reality applications for supporting human-robot interactive cooperation. *Procedia CIRP*, 100:79–84, 2022. Accessed: 2024-09-16.
- [14] Michael D. Covert, Tiffany Lee, Ivan Shindev, and Yu Sun. Spatial augmented reality as a method for a mobile robot to communicate intended movement. *Computers in Human Behavior*, 34:241–248, 2014.
- [15] P. Daponte, L. De Vito, and F. Picariello. State of the art and future developments of the augmented reality for measurement applications. *IEEE Transactions on Instrumentation and Measurement*, 69(2):455–466, 2020. Accessed: 2024-09-16.
- [16] K. Filus and P. Klakowicz. Real-time testing of vision-based systems for agvs with aruco markers. *Journal of Intelligent & Robotic Systems*, 105(1):17–32, 2023. Accessed: 2024-09-16.
- [17] J. Husar and K. Wrona. Possibilities of using augmented reality in warehouse management: A study. *International Journal of Production Research*, 60(14):4128–4140, 2022. Accessed: 2024-09-16.
- [18] J. Fu, A. Rota, S. Li, J. Zhao, Q. Liu, E. Iovene, G. Ferrigno, and E. De Momi. Recent advancements in augmented reality for robotic applications: A survey. *Actuators*, 12(8):323, 2023. Accessed: 2024-09-16.
- [19] Z. Makhataeva and H. A. Varol. Augmented reality for robotics: A review. *Robotics*, 9(2):21, 2020. Accessed: 2024-09-16.
- [20] Moraneus. Python flask: A comprehensive guide from basic to advanced. *Medium*, Mar 2024. Accessed: 2024-09-28.
- [21] Asian Digital Hub. What is node.js and how it work? *Medium*, Dec 2023. Accessed: 2024-09-28.
- [22] MDN Web Docs. Websockets and real-time web applications. 2024. Accessed: 2024-09-28.

-
- [23] Tonino Jankov. Nginx vs apache: Web server showdown. *Kinsta®*, Jun 2019. Accessed: 2024-09-28.
 - [24] N. Maupin and N. Maupin. How do ultrasonic sensors work? <https://howdowork.com/technology/computers-electronics/ultrasonic-sensors-working/#:~:text=How%20Do%20Ultrasonic%20Sensors%20Work%20Ultrasonic%20sensors%20work,they%20are%20partially%20reflected%20back%20to%20the%20sensor.>, September 2023. Accessed: 2024-09-21.
 - [25] G. Benet, F. Blanes, J.E. Simó, and P. Pérez. Using infrared sensors for distance measurement in mobile robots. *Robotics and Autonomous Systems*, 40(4):255–266, Sep 2002.
 - [26] rhydoLABZ. Dagu compound infrared sensor. 2024. Accessed: 2024-09-28.
 - [27] T. Yang et al. 3d tof lidar in mobile robotics: A review. *arXiv*, 2022. Accessed: 2024-09-28.
 - [28] 'G.C. La Delfa', 'V. Catania', 'S. Monteleone', 'J.F. De Paz', and "J. Bajo". Computer vision based indoor navigation: A visual markers evaluation. In *Ambient Intelligence - Software and Applications*, pages 165–172. Springer, 2015.
 - [29] D. Divani I. Jacobsen, F. Supty. Remote-controlled camera robot. In *BCIT Capstone Project Report*. BCIT, 2018.
 - [30] R. Selvarasu M. Vanitha, M. Selvalakshmi. Monitoring and controlling of mobile robot via internet through raspberry pi board. In *2016 Second International Conference on Science Technology Engineering and Management (ICONSTEM)*, pages 462–463. IEEE, 2016.

ADC/DAC CORE

A.1 A USEFUL SUB APPENDIX

Put your appendix stuff here.