AN-NAJAH NATIONAL UNIVERSITY

FACULTY OF ENGINEERING AND INFORMATION TECHNOLOGY

COMPUTER ENGINEERING DEPARTMENT

MazeSolver

Hardware Graduation Project

Presented in partial fulfillment of the requirements for the Bachelor's degree in Computer Engineering

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Disclaimer

This report has been prepared as part of the requirements for the Bachelor's degree. The views, findings, and conclusions presented are solely those of the authors and do not necessarily represent those of the university or the supervisor.

Abstract

This project entails designing and constructing an autonomous robot, MazeSolver, to solve mazes using the Flood Fill algorithm. Motivated by the rising significance of autonomous navigation in disaster response, smart manufacturing, and logistics automation, the objective is to demonstrate real-time decision-making through sensor feedback and algorithmic path planning [3, 4, 5]. The robot employs three IR sensors and a VL53L0X Time-of-Flight LiDAR for environmental mapping, dynamically updating its internal map upon detecting obstacles [15, 16]. Utilizing the Flood Fill algorithm, it adapts its path in real-time, striving to select the shortest route despite an initially unknown maze layout.

Development involved hardware design with an ESP32 microcontroller, sensor calibration, programming in Arduino C++, and testing in a physical 7x6 maze, with movement controlled by two DC motors with encoders via an L298N driver and orientation maintained by an MPU6050 gyroscope [9, 12]. Communication is facilitated by a remote unit with a second ESP32 using the ESP-NOW protocol [1]. MazeSolver distinguishes itself from predecessors like Micromouse through its real-time wall detection and dynamic replanning, enhancing adaptability for applications such as warehouse robots, search-and-rescue units, and agricultural machines in unpredictable environments.

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Chapter 1

Introduction

The MazeSolver project was conceived from a fascination with autonomous systems and their application in solving real-world navigational challenges. The name "MazeSolver" directly reflects its primary mission: to autonomously navigate and find the most efficient path through a physical maze. This capability is crucial in applications where robots must operate in unknown or changing environments, such as automated warehouses, robotic vacuum cleaners, or search-and-rescue units [5].

We chose a two-wheeled differential drive robot over other designs for its simplicity, maneuverability, and efficiency in navigating tight spaces typical of mazes. While legged robots offer superior terrain adaptability, a wheeled platform is more than sufficient for the flat surfaces of a maze and allows for a greater focus on the algorithmic and sensor-based aspects of the project.

Central to our navigation strategy is the **Flood Fill algorithm** [3, 4, 6]. This algorithm works by assigning a value to each cell in the maze, representing its distance from the target cell. The robot then simply moves from a higher-value cell to an adjacent lower-value cell, guaranteeing the shortest path based on the currently known map [5]. Its key advantage is its ability to dynamically re-calculate these values whenever a new wall is discovered, allowing the robot to adapt its path in real-time—a feature we tested using servo-controlled walls set to open or closed states before the robot's exploration.

From a hardware perspective, MazeSolver is built around the powerful **ESP32 microcontroller**. This choice was driven by its dual-core processor, ample GPIO, and built-in Wi-Fi, which we leveraged for the **ESP-NOW** communication protocol [1, 2]. This protocol provides a low-latency, direct link between the robot and a custom-built remote control, allowing for setting goal coordinates and manipulating the maze's servo-controlled walls before exploration begins. The robot's movement is handled by two DC motors with encoders, driven by an **L298N H-bridge**, a robust and widely-used driver in robotics [9, 10].

To perceive its environment, the robot is equipped with three IR sensors for detecting walls to its front, left, and right, and a **VL53L0X Time-of-Flight (ToF) LiDAR sensor** for more precise distance measurements [15, 16]. An **MPU6050** Inertial Measurement Unit (IMU) is used to track the robot's orientation, providing essential data for accurate turns and maintaining stability [12, 13]. Together, this suite of sensors provides the rich data needed for the Flood Fill algorithm to build an accurate map of the maze and navigate effectively.

Chapter 2

Theoretical Background and Previous Work

The field of autonomous maze-solving robots is well-established, with competitions like Micromouse driving innovation for decades [5]. Early and simple approaches often rely on algorithms like the "wall-follower" rule, where the robot consistently follows either the left or right wall [17]. While easy to implement, this method does not guarantee finding the shortest path and can fail in mazes with island loops.

More advanced solutions employ graph traversal algorithms such as Breadth-First Search (BFS) or Depth-First Search (DFS) to explore the maze [7]. However, for finding the optimal path, algorithms like Dijkstra's or A* are commonly used [6]. These algorithms are powerful but can be computationally intensive for the limited processing capabilities of microcontrollers like the ESP32, often requiring a complete map of the maze before calculating the shortest path.

Our project focuses on the **Flood Fill algorithm**, which is particularly well-suited for maze-solving in unknown environments [3, 4, 5, 6]. It is a dynamic programming approach where the maze is modeled as a grid. Each cell is assigned a value corresponding to its distance from the goal. The goal cell is initialized to 0, its neighbors to 1, their neighbors to 2, and so on, "flooding" the entire maze. As the robot explores, it stores the state (open or closed) of walls for each cell and updates its map. If it encounters an unexpected wall, it updates the map and triggers a new "flood" to recalculate cell values, dynamically finding a new shortest path. This method is highly efficient for Micromouse competitions where the robot performs an exploration run followed by a speed run [4, 5].

Previous student projects and academic papers have demonstrated the feasibility of using microcontrollers like Arduino or ESP32 for maze-solving tasks [8, 5]. Many of these projects utilize IR or ultrasonic sensors for wall detection. Our work builds upon these foundations by integrating a ToF LiDAR sensor for more accurate distance data and implementing the more complex Flood Fill algorithm for dynamic replanning. Furthermore, the use of the ESP-NOW protocol for remote interaction and control of a maze with pre-set servo-controlled walls represents a novel feature compared to many standard maze-solver projects [1, 6].

Chapter 3

Methodology

This chapter describes the theoretical foundations, hardware implementation, and software architecture of the MazeSolver project.

3.1 Theory

3.1.1 The Flood Fill Algorithm

The core of the robot's intelligence is the **Flood Fill algorithm**, adapted for pathfinding [3, 4, 5]. The maze is represented as a 2D array (e.g., 7x6). Each cell in the array stores a distance value and the state of its walls (open or closed). The algorithm works as follows:

1. **Initialization:** The goal cell is assigned a value of 0. All other cells are initialized to a high value (e.g., 255).
2. **Flooding:** A queue is created, and the goal cell is added to it. While the queue is not empty, a cell is dequeued. For each of its neighbors that is not blocked by a wall and has a value higher than the current cell's value + 1, its value is updated, and it is added to the queue. This process continues until the entire maze is "flooded" with distance values [3].
3. **Navigation:** The robot, at any given cell, checks the values of its accessible neighbors (front, left, right). It always chooses to move to the neighbor with the smallest distance value [5].
4. **Dynamic Replanning:** If the robot's sensors detect a wall where one was not expected, it updates its internal wall map with the wall's state (open or closed). It then re-initiates the flood-fill process to update all cell values based on the new map, thus dynamically finding a new shortest path [4, 6].

3.1.2 Motor Control and Odometry

Movement is controlled via the **L298N motor driver**, which allows for precise control over the speed and direction of the two DC motors [9, 10]. The **ESP32** generates PWM (Pulse Width Modulation) signals to control motor speed. Encoders on the motors provide feedback on wheel rotation, which is used for basic odometry to track the distance traveled and ensure straight movement and accurate turns. An **MPU6050 IMU** provides gyroscopic data to correct for rotational errors during turns, ensuring the robot maintains a consistent heading (e.g., 90-degree turns) [12, 13].

3.2 Software

The robot's software, written in C++ using the Arduino IDE, is modular.

- **Main Controller (Robot):** The primary **ESP32** runs the main control loop. It manages sensor readings, executes the **Flood Fill algorithm**, controls the motors via the **L298N driver**, and communicates with the remote control using **ESP-NOW** [1].
- **Sensor Fusion:** Data from the three IR sensors and the **VL53L0X LiDAR** are processed to create a reliable understanding of the immediate surroundings. The IR sensors provide binary wall-or-no-wall information, while the LiDAR gives precise distance, useful for centering the robot within a corridor [15, 17].
- **Flood Fill Module:** A dedicated class handles all aspects of the algorithm: storing the maze grid, managing wall data (open or closed), running the flooding logic, and providing the next best move to the main controller [3, 5].
- **Motor Control Module:** This module abstracts the low-level PWM commands for the **L298N driver** into high-level functions like `moveForward()`, `turnLeft()`, and `turnRight()`. It incorporates feedback from the **MPU6050** to ensure accurate turns [13].
- **ESP-NOW Communication:** The robot has an ESP-NOW callback function (`onDataRecv`) that listens for commands from the remote. It can receive new goal coordinates or commands to update the state of the servo-controlled walls before exploration begins. It also sends its current position and status back to the remote [2].

3.3 Hardware

The hardware system is composed of several key components integrated to achieve the project's goals.

1. **ESP32 Dev Kit:** A powerful microcontroller with a dual-core processor and built-in Wi-Fi/Bluetooth capabilities. It serves as the brain of the robot, running all the core logic [8].

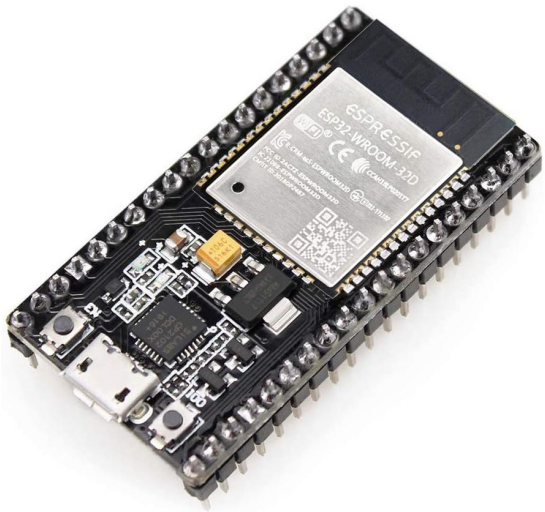

Figure 3.1: ESP32 Dev Kit

2. **VL53L0X ToF LiDAR Sensor:** This sensor measures distance using the time it takes for a laser pulse to reflect off an object. It provides accurate distance readings (up to 2m), which are used for precise positioning within maze corridors and for more reliable obstacle detection than IR sensors alone [15, 16].

3. **IR Sensors (x3):** Used for basic wall detection. One sensor faces forward, one left, and one right. They provide quick, binary feedback on the presence of obstacles in adjacent cells [17].

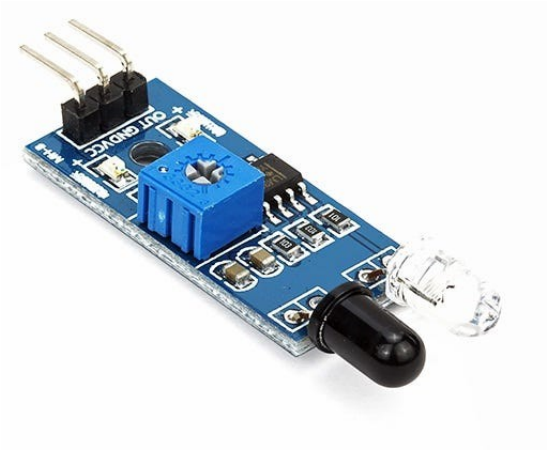

Figure 3.2: IR Sensors

4. **MPU6050 Gyroscope/Accelerometer:** An IMU that measures angular velocity and acceleration. It is crucial for implementing accurate turns and can be used for balance control if the robot design were to change [12, 13].

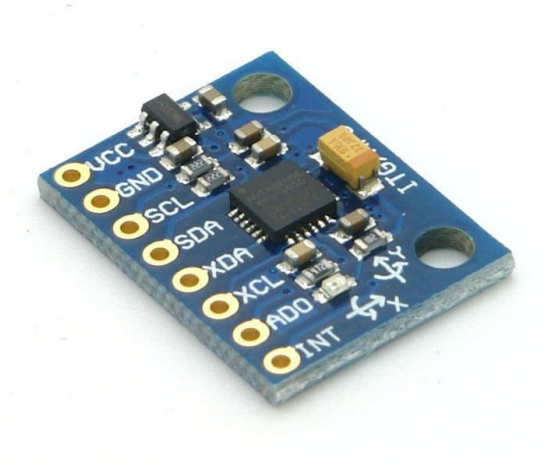

Figure 3.3: MPU6050 Gyroscope/Accelerometer

5. **DC Motors with Encoders (x2):** These provide the robot's locomotion. The encoders give feedback on wheel rotation, allowing for closed-loop control of distance and speed.

6. **L298N Motor Driver:** A dual H-bridge driver that takes control signals from the ESP32 and delivers the higher current required to run the DC motors. It allows for control of both speed and direction [9, 10].

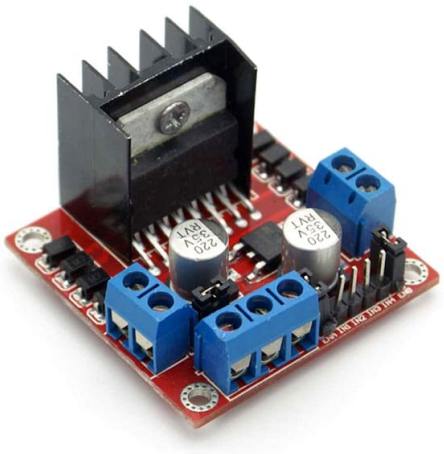

Figure 3.4: L298N Motor Driver

7. **Power Supply:** Two 9V batteries are used to power the system. The first 9V battery directly powers the L298N motor driver, ESP32 microcontroller, and DC motors with encoders. The second 9V battery is connected to an **XL4015 voltage regulator** to step down the voltage to 5V, powering the three IR sensors, MPU6050 IMU, and VL53L0X LiDAR sensor for stable operation [11].

Figure 3.5: XL4015 Voltage Regulator

8. **Remote Control Unit:**
   - **ESP32:** A second ESP32 acts as the controller for the remote [8].
   - **Keypad:** Allows the user to input goal coordinates (row, column).

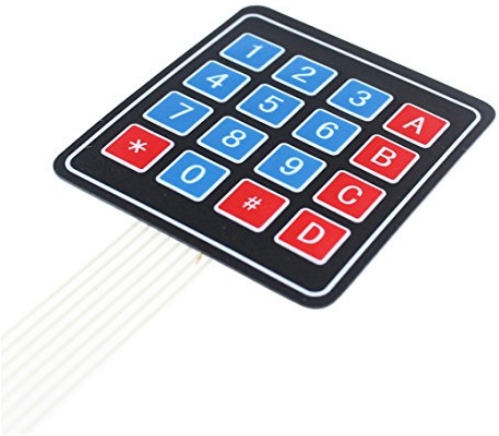

Figure 3.6: Keypad

- **LCD 16x4:** Displays system status, current robot position, and prompts for user input.

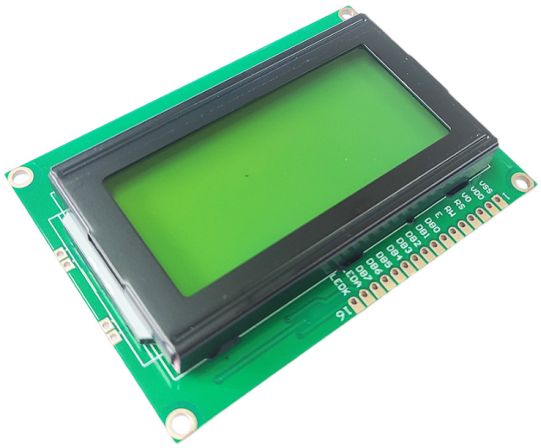

Figure 3.7: LCD 16x4

9. **Dynamic Maze:** A 7x6 physical maze with three walls that can be opened or closed by servo motors before the robot begins exploration, controlled by a third ESP32 that receives commands from the remote control [1].

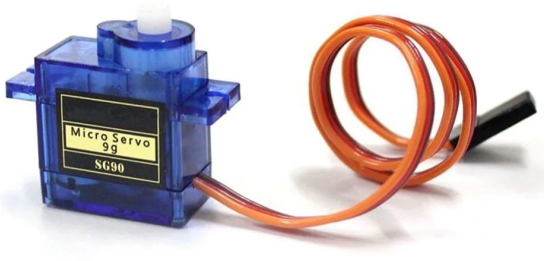

Figure 3.8: Servo Motor

Chapter 4

Results and Analysis

The MazeSolver project successfully demonstrated its core capabilities through a series of practical tests in a physical 7x6 maze.

1. **Maze Solving and Pathfinding:** The robot consistently and successfully navigated from a starting point to a user-defined endpoint. The implementation of the **Flood Fill algorithm** proved highly effective [3, 5]. In its initial run through an unknown maze, the robot explored, mapped walls (storing their open or closed states), and reached the goal. On subsequent runs, after the maze was mapped, the robot took the mathematically shortest path without any exploratory detours.

2. **Wall Configuration Adaptation:** A key achievement was the robot's ability to navigate a maze with pre-set servo-controlled walls. We tested this by configuring the maze with different wall states (open or closed) before exploration began, using the remote to set the positions of three servo-controlled walls. The robot accurately detected and stored the wall states as it explored, updating its internal map and using the **Flood Fill algorithm** to calculate the optimal route to the goal [4, 6]. This validates the algorithm's ability to handle varying maze configurations set prior to exploration.

3. **Sensor Performance:** The combination of IR sensors and the **VL53L0X LiDAR sensor** was effective. The IR sensors provided rapid detection of walls for the algorithm, while the LiDAR sensor's precise measurements were used to keep the robot centered in corridors, preventing collisions with walls during movement [15]. The **MPU6050** was critical for executing clean 90-degree turns, a fundamental requirement for grid-based navigation [13].

4. **Remote Control and Communication:** The **ESP-NOW** communication protocol provided a reliable and low-latency link between the remote control and the robot [1, 2]. Goal coordinates and wall configuration commands were transmitted successfully before exploration, and the robot sent back real-time updates of its position, which were displayed on the remote's LCD. This created a complete, interactive user experience.

Chapter 5

Discussion

The MazeSolver project provided a comprehensive exploration into the design and implementation of an autonomous navigation system.

5.1 Performance Interpretation and Design Effectiveness

The successful implementation of the **Flood Fill algorithm** was the cornerstone of this project's success. Its ability to find the shortest path by storing and updating wall states during exploration makes it a superior choice for real-world applications compared to static algorithms like wall-followers or A* (when used on a pre-defined map) [3, 5, 6].

The choice of the **ESP32** was validated by its performance. Its processing power was more than adequate for running the **Flood Fill algorithm** and managing sensor data simultaneously [8]. Furthermore, its native support for **ESP-NOW** was a significant advantage, simplifying the implementation of wireless communication and eliminating the need for a router-based network [1].

The multi-sensor approach proved robust. Supplementing IR sensors with a **ToF LiDAR sensor** provided the accuracy needed for fine-tuned movements and reliable mapping [15, 16].

5.2 Comparison with Previous Work

Compared to many introductory maze-solving robots that use simple wall-following algorithms, MazeSolver represents a significant step up in intelligence by implementing a true shortest-path algorithm [17, 5]. While many advanced projects use A* or Dijkstra's algorithm, our use of **Flood Fill** is particularly tailored to the "unknown maze" problem, which is a classic challenge in robotics competitions like Micromouse [4, 6]. The addition of a maze with pre-set servo-controlled walls and a dedicated remote control system are features that distinguish this project from standard academic examples.

5.3 Implications and Future Directions

This project serves as a solid foundation for more advanced autonomous systems. The principles of sensor fusion, dynamic path planning, and wireless control are directly applicable to more complex challenges. Future work could expand upon the current capabilities:

- **Advanced Sensor Fusion:** Integrate a camera (like an **ESP32-CAM**) to use computer vision for landmark detection or QR code reading within the maze, adding another layer of data for navigation [8].

- **PID Control for Speed:** Implement a full PID (Proportional-Integral-Derivative) controller for the motors, using the encoder feedback to maintain precise speeds and handle variations in load or battery voltage more effectively.
- **Energy Efficiency:** Implement power-saving modes for the **ESP32** and sensors, allowing the robot to operate for longer periods on a single battery charge.
- **Multi-Robot Collaboration:** Expand the **ESP-NOW** network to include multiple robots that could collaborate to solve a larger maze more quickly, sharing map data with each other in real-time [1].

5.4 Constraints

The MazeSolver project, while successful in demonstrating autonomous maze navigation, faced several constraints that impacted its design, implementation, and performance. Below, we outline the key constraints identified during development and testing, along with additional potential constraints based on the project's scope.

- **Motor and Driver Limitations:** The DC motors are sensitive to voltage drops, requiring a fully charged 9V battery for consistent performance. The **L298N motor driver** generates heat during prolonged operation, which may limit operational duration without additional cooling or more efficient drivers [10].
- **Power Supply Limitations:** The use of two 9V batteries limits the robot's runtime due to finite battery capacity. The absence of built-in power-saving modes could lead to rapid depletion during extended operation [11].
- **Sensor Constraints:** IR sensors are affected by variability in surface reflectivity and ambient light, which can compromise their reliability. The VL53L0X LiDAR sensor provides accurate distance readings up to 2m, but its range and precision may be limited in larger mazes or under certain lighting conditions [15, 17].
- **Flood Fill Algorithm Limitations:** The Flood Fill algorithm assumes a grid-based structure, limiting its applicability to non-grid environments. It is optimized for small mazes like the 7x6 grid used, but becomes computationally intensive for larger grids due to the need to process more cells during flooding [3, 5].
- **Terrain Assumptions:** The design assumes flat maze surfaces, making it unsuitable for uneven terrain or outdoor environments without significant modifications.
- **Development Time:** The project timeline, constrained by bachelor's degree requirements, limited the depth of testing and feature implementation, such as full PID control or machine learning integration.
- **Exploration Time:** The initial exploration run in an unknown maze requires time to map walls and their states (open or closed), delaying optimal pathfinding until subsequent runs

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

The MazeSolver project successfully achieved its objective of creating an autonomous robot capable of intelligently navigating and solving a maze with pre-set servo-controlled walls. The project demonstrated the feasibility and effectiveness of using the **Flood Fill algorithm** for real-time, adaptive pathfinding in an unknown environment [3, 5, 6].

Key conclusions from this project include:

- **Effective Algorithmic Control:** The **Flood Fill algorithm** is a powerful and highly suitable choice for maze-solving robots, particularly for unknown mazes with fixed wall configurations [4].
- **Robust Hardware Integration:** The combination of an **ESP32 microcontroller**, a suite of complementary sensors (IR, LiDAR, IMU), and reliable motor drivers (**L298N**) provides a capable and cost-effective platform for autonomous robotics [8, 9].
- **Seamless Wireless Communication:** The **ESP-NOW protocol** is an excellent solution for low-latency, direct device-to-device communication in robotics projects, enabling complex interactions without the overhead of traditional Wi-Fi networks [1, 2].
- **Validation of Design:** The robot's ability to solve the maze, find the shortest path, and adapt to pre-set wall configurations validates the overall design and integration of its hardware and software components.

6.2 Recommendations for Future Work

Building on the success of this project, the following recommendations are proposed for future enhancements:

- **Implement Full PID Control:** Develop and tune a PID control loop for the motors to achieve smoother acceleration and more precise speed regulation, making movement more reliable and efficient. Consider integrating real-time sensor feedback from the encoders and MPU6050 to dynamically adjust PID parameters, potentially using a Kalman filter to reduce noise and improve stability during rapid turns or uneven surfaces.
- **Enhance the User Interface:** Develop a mobile application to serve as the remote control, offering a graphical interface for setting goals and visualizing the robot's progress on a map in

real-time. Extend this by adding features such as live video streaming using an ESP32-CAM module, customizable alert notifications for obstacles or path changes, and a history log of past maze-solving runs for analysis.

- **Enhance Sensor Suite:** Upgrade the sensor array by adding a low-cost camera module (e.g., OV7670) for visual recognition of maze features, such as color-coded walls or checkpoints, and integrate a more precise IMU (e.g., MPU9250) to improve orientation tracking in dynamic environments. This could enable advanced features like 3D mapping or obstacle avoidance beyond wall detection.
- **Incorporate RFID Localization:** Integrate an RFID reader under the robot and place RFID tags on each maze cell to enable precise localization. By reading the unique ID of the tag in a cell, the robot can instantly determine its position, improving navigation accuracy and reducing reliance on odometry or sensor-based position estimation. This could enhance the Flood Fill algorithm's efficiency by providing reliable starting and current position data.

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Appendix A

Project Disclaimer

This disclaimer clarifies the context and responsibility for the content presented in this graduation project report.

DISCLAIMER

This report was prepared by student(s) of the Computer Engineering Department, Faculty of Engineering, An-Najah National University, as part of their graduation project requirements. While every effort has been made to ensure accuracy and thoroughness, the views, conclusions, and recommendations expressed herein are solely those of the student author(s). An-Najah National University and the Computer Engineering Department accept no responsibility or liability for the consequences of this report being used for any purpose other than that for which it was originally commissioned.

Appendix B

Citation Style

All references in this report adhere strictly to the Institute of Electrical and Electronics Engineers (IEEE) citation style. This standard ensures consistent formatting for in-text citations and the comprehensive reference list, encompassing academic journals, books, technical documents, and open-source software utilized in this project.