

AUTONOMOUS WIRE INSPECTION UNIT



By

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Supervised By

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Department of Computer Engineering
Bahria University Islamabad

2026

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Submitted to the Department of Computer Engineering in the partial fulfillment of the requirements for the degree of Bachelors in Computer Engineering.

**Department of Computer Engineering
Bahria University Islamabad**

2026



BAHIRA UNIVERSITY
DEPARTMENT OF COMPUTER ENGINEERING

Dated: 04-06-2026

CERTIFICATE

We accept the work contained in the report titled “**Autonomous Wire Inspection Unit (AWIU)**” as a confirmation to the required standard for the partial fulfillment the degree of Bachelor of Computer Engineering.

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AUTONOMOUS WIRE INSPECTION UNIT

SDG No	Description of SDG	SDG No	Description of SDG
SDG 1 ✓	No Poverty	SDG 9 ✓	Industry, Innovation, and Infrastructure
SDG 2 ✓	Zero Hunger	SDG 10	Reduced Inequalities
SDG 3	Good Health and Well Being ✓	SDG 11	Sustainable Cities and Communities
SDG 4	Quality Education	SDG 12	Responsible Consumption and Production
SDG 5	Gender Equality	SDG 13	Climate Change
SDG 6	Clean Water and Sanitation	SDG 14	Life Below Water
SDG 7	Affordable and Clean Energy	SDG 15	Life on Land
SDG 8 ✓	Decent Work and Economic Growth	SDG 16 ✓	Peace, Justice and Strong Institutions
		SDG 17	Partnerships for the Goals



Range of Complex Problem Solving			
	Attribute	Complex Problem	
1	Range of conflicting requirements	Involve wide-ranging or conflicting technical, engineering and other issues.	
2	Depth of analysis required	Have no obvious solution and require abstract thinking, originality in analysis to formulate suitable models.	✓
3	Depth of knowledge required	Requires research-based knowledge, much of which is at, or informed by, the forefront of the professional discipline and which allows a fundamentals-based, first principles analytical approach.	✓
4	Familiarity of issues	Involve infrequently encountered issues	
5	Extent of applicable codes	Are outside problems encompassed by standards and codes of practice for professional engineering.	
6	Extent of stakeholder involvement and level of conflicting requirements	Involve diverse groups of stakeholders with widely varying needs.	✓
7	Consequences	Have significant consequences in a range of contexts.	
8	Interdependence	Are high level problems including many component parts or sub-problems	
Range of Complex Problem Activities			
	Attribute	Complex Activities	
1	Range of resources	Involve the use of diverse resources (and for this purpose, resources include people, money, equipment, materials, information and technologies).	
2	Level of interaction	Require resolution of significant problems arising from interactions between wide range and conflicting technical, engineering or other issues.	
3	Innovation	Involve creative use of engineering principles and research-based knowledge in novel ways.	✓
4	Consequences to society and the environment	Have significant consequences in a range of contexts, characterized by difficulty of prediction and mitigation.	✓
5	Familiarity	Can extend beyond previous experiences by applying principles-based approaches.	

UNDERTAKING

I certify that the research work titled “Autonomous Wire Inspection Unit” is our own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources, it has been properly acknowledged and referred to.



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DEDICATION

This thesis is dedicated to our parents, especially Asghar Shahzad and Sobia Irum, our teachers, supervisor, siblings, relatives, and everyone who supported us throughout the development of this Final Year Project. Their encouragement, guidance, and unwavering support inspired us to complete a practical engineering prototype that addresses a real-world inspection and safety challenge.

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We also express our sincere thanks to the Department of Computer Engineering, Bahria University Islamabad Campus, for providing the academic environment required to complete this work. We are thankful to our families for their patience, prayers, and encouragement. Finally, we acknowledge the support of our classmates and friends who assisted us during discussions, testing, documentation, and presentation preparation.

ABSTRACT

Frequently, faults can be hard to spot in underground and tunnel based electrical wiring systems and may require time-consuming excavation or manual examination. The design and development of an Autonomous Wire Inspection Unit (AWIU) which uses a tracked robotic rover, non-contact AC field sensing, an encoder-based distance measurement, wireless movement control and real-time video monitoring for detecting and locating faults in a single underground or tunnel based electrical line is presented. The aim of our proposed system is to reduce human intervention into unsafe areas in the tunnel and provide a low-cost system to determine possible location of a wire break. The hardware architecture of our system comprises of an ESP32 Dev Module, ESP32-CAM, L298N motor driver, tracked rover chassis, battery supply and a non-contact voltage detection circuit including a spiral pickup antenna and three BC547 amplification stages. The ESP32 is a perfect choice for this prototype because of its Wi-Fi and Bluetooth (Bluetooth Radio) capabilities and embedding power-processor capabilities is achieved with low power consumption and the control of inductive DC motor loads, is supported by the L298N motor driver. The methodology is prototype-driven engineering process, with the following testing sequence: testing of the sensing circuit, motor control, communication links, encoder feedback, and video stream, before integration. The principle of detection is by the presence or absence of the electromagnetic field around an energized conductor. If there is a field listed, then the wire will be assumed to be continuous. If the field is lost, then a possible fault event is identified and the distance travelled is noted as the fault location. The rover and the remote-control, real-time video monitoring, wireless voltage sensing and fault indication are functionally tested. It is demonstrated how the system can be used practically for safe underground wire monitoring.

Keywords: Autonomous Wire Inspection Unit, tunnel inspection rover, underground cable fault detection, non-contact AC voltage detection, Bluetooth control, Wi-Fi video streaming, fault localization.

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Chapter 1

Introduction

1.1 Background

In our project, titled the Autonomous Wire Inspection Unit, we focus on underground systems, conduits, and tunnel service spaces where electrical cables play a critical role in residential infrastructure, commercial and industrial power distribution. They are not visible to the naked eye, which helps prevent them from being affected by the weather or damaged by a slight touch; however, if there is a fault, they are not easily accessible. A failure of one conductor can disrupt power supply, halt equipment operation, pose hazardous safety conditions and lead to higher maintenance expenses[1]. It may be more difficult to find the fault point than to ensure the fault exists since the damaged area is not visible. A range of traditional underground cable fault detection techniques exist, such as continuity testing, insulation resistance testing, thumper-based tracing, bridge methods and time domain reflectometry. Time domain reflectometry is commonly used because it sends a pulse into a cable and measures the reflected wave based on changes in the cable's impedance to determine the distance of the fault[2].

However, at a cable end or break the reflected pulse can provide an approximate indication of the location of the break, but still requires access to be suitable, the pulse to be correctly interpreted, and test equipment to be appropriate. Our proposed project will solve this problem by integrating robotic mobility with non-contact electrical field sensing. A small rover, which traverses the cable path and measures the electromagnetic field emitted by a live AC cable, replaces the need for a worker to go into a tunnel or dig along the cable path. If the field exists, the system considers the line segment to be "active." If the field is not found, the rover records the location as a potential breakage area[3]. Motor encoder feedback is used to determine distance travelled and the operator can determine the approximate fault location based on the point of entry.

Our project is not just about fault detection; it has engineering value. It also shows how to combine sensing, motor control, wireless communication, video streaming, user interface design and distance measurement in an integrated embedded system. For embedded prototypes, the ESP32 family is suitable since the ESP32 microcontroller in-

cludes built-in Wi-Fi and Bluetooth technology. The ESP32-CAM also enables low-cost vision-based monitoring thanks to the ESP32 platform, the built-in camera and Wi-Fi module for prototype Internet of Things applications[4].



Fig. 1.1: Body structure

For underground wiring systems the issue is much more complicated because the cables are not always in a straight line and are not easily reachable. Electrical wires can be installed in bends, narrow areas, enclosed duct and areas that are hard to see in many buildings, factories and service tunnels. Inside such routes, if there is a break, the repair team may not be able to determine the exact area of the break. This can lead to sub-optimal wall openings, floor openings, conduits or tunnel sections. Thus, such a system, which can navigate through the path of the inspection and estimate the approximate

distance to the fault, can facilitate quicker decisions in maintenance. The need for this system is also associated with the growing automation in inspection and maintenance. In modern times, engineering systems are shifting towards sensor-based inspection, remote monitoring and robot assistance, rather than manual checking.

Similarly, the Autonomous Wire Inspection Unit is a mobile rover with a non-contact detection circuit, in the same direction. It is not necessary to make direct contact with the conductor, making it safer for controlled inspection work. It also offers a video feedback so the operator can see the route while it's being moved. The concept of the project is very simple. When the AC wire is live, it emits an electric field around it. If the wire is continuous, then the sensing circuit can sense this field. When the wire is broken, the field disappears after the break point. The rover runs along the wire path and keeps track of this field. The system can infer that field loss has occurred and that area is possibly the cause of the fault as soon as it loses the field. This principle is particularly appropriate for a single-wire controlled model where the position of the wire and the route it needs to follow is already known.

1.2 Problem Statement

Flaws in hidden electrical wires are hard to find in underground pipes, non-metallic conduits and in tunnels. Electrical testing can confirm a break in a cable but may not necessarily tell you the exact physical location of the break. This means that before the fault is identified, utility staff and maintenance crews might have to travel long stretches of cable, enter a confined space or dig in an area. These activities delay repairs, add to repair costs and create safety hazards. The problem becomes more serious when the path of the cable is within a tunnel or conduit where it is not safe or convenient to inspect the cable directly. Human inspection can present a worker with the hazards of confined space, lack of visibility, live electrical lines, unstable surfaces and the environment[5]. Therefore, a mobile system of inspection without contacts and an estimated measurement of a probable point of breakage is necessary and should be low cost.

Another issue is that traditional inspection methods tend to divide the electrical and physical inspection. For instance, a fault detection instrument may discover that there's a fault, but the technician will still need to correlate the measured value with the cable route. This is challenging if the path is set behind a fence or is curved or set in a tunnel. This gap is addressed by the proposed project moving and documenting the distance

along the physical pathway. This allows for the inspection result to be more easily understood since the fault indication is associated with the travelled distance of the rover.

The issue is also one of safety, of view. w. Manual inspection around electrical wires can lead to electric shock, inadequate lighting, limited space for workers to move around and accidental contact with damaged insulation. These risks are greater if inspection is undertaken in an underground or tunnel based environment. The project is therefore meeting a practical need for safety as the operator is able to control the rover remotely. The camera stream also enables the operator to view the rover's surroundings without having to walk into the inspection path.

Cost is a problem as well. While effective, industrial cable fault location systems can be costly to students, small laboratories, small-scale maintenance teams or demonstration areas. The use of common components like the ESP32 module, ESP32-CAM module, L298N motor driver, encoder motors and a transistor-based sensing circuit is the basis of this project. This is an inexpensive, easily reproducible prototype to use for academic purposes.

1.3 Aim of the Project

Improving the inspection process – also in terms of minimising uncertainty – is also part of the aim. The system makes an attempt to relate the fault indication with an measured distance rather than just indicating the status as active or inactive. This makes the output more useful in that the operator will be able to get an idea of where the inspection should be focused. The project will thus seek to demonstrate in a practical manner the potentiality of combining sensing and mobility for wire inspection.

This is not intended to be a commercial certified cable fault locator. Rather, a working prototype to prove the concept of independent or semi-independent inspection is to be developed and tested. System for controlled conditions, educational testing and low cost demonstration. This project is well suitable for the final year engineering project because it involves Hardware Development, Software Programming, Circuit Testing, Wireless Communication and System Integration.

1.4 Objectives

The objectives of this project are:

- Design and construct a small, tracked rover capable of traveling on an inspection path, like a tunnel.
- Construct a high gain non-contact AC voltage detector with a spiral pickup wire and amplification stages of transistors.
- Use an ESP32 Dev Module to handle pulse train data from encoders, sensor data, and control to move the robot.
- Estimate the distance travelled by the rover using encoder motors to help with fault localization.
- Use an ESP32-CAM module to send video data over Wi-Fi in real time.
- Create a mobile app with movement control, real-time status, distance tracking and camera viewing. Evaluate prototypes using subsystem and integrated testing.

The project is also committed to system integration, with the aim of creating a unified solution that integrates all the necessary elements. All subsystems play a different role but the overall value of the project is dependent on all subsystems. The rover body offers movement; the motor driver offers power to the motors; the ESP32 takes care of commanding the rover and processing sensor input; the encoder motors provide distance information; the sensing circuit detects the AC field; and the ESP32-CAM offers live monitoring and control of the rover by the operator through the mobile application. This integration enables the project to be more complete than a mere wire detector.

A further goal is to determine if the task of inspection can be done usefully with a low cost prototype. The system should be "tuned up" in a step by step fashion, from movement of the motors, to response of the sensors, to reading of the encoders, to streaming of the camera and finally integrated operation. This testing method is used to determine if the system is able to sense the field, track it reliably and display an approximate fault distance.

1.5 Scope of Project

Our project is intended for a single-wire system installed in underground PVC conduit, non-metallic conduit or inspection tunnels such as tunnels. It is not designed to test multi-core shielded power cables, high-voltage distribution networks or metallic powerways which can cause a substantial distortion of the sensed field. Our prototype does not require the sensing circuit to strip away the conductor's insulation or make physical contact with the conductor, as the insulation is detected with the help of non-contact field detection[6]. Movement of rover, Manual wireless control, Live video monitoring, Measurement of distance, Fault indication. Our prototype is a proof-of-concept system to be used for a controlled system test. It is not intended to replace industrial certified instruments for testing and locating cable faults. For industrial use, the calibration would need to be increased, rugged packaging, electrical safety certification, improved communication range and testing under actual cable route conditions would need to be done[7].

The project scope also covers, not autonomous navigation, but manual, wireless operation. The operator uses the rover by operating it via a mobile application. This selection makes the system simple and reliable to test prototypes. Obstacle detection, route planning and more advanced control algorithms would be needed for full autonomous movement, and are not included in the scope of the current project. In the future, however, the present design can be the base for autonomous inspection.

The system is intended for the short-range inspection. If it is a controlled laboratory or demonstration setup, Bluetooth and Wi-Fi are possible methods of communication but if the range is longer, more potent methods of communication may be necessary. Likewise, the battery system is a good test system, but would require enhancement for extended field use. The limitations are not a problem as the primary goal of the project is to provide evidence of the working concept.

Table 1.1: Summary of research problem and proposed response

S.No.	Problem Area	Practical Issue	Project Response
1	Hidden wire breakage	Fault point is not visible inside tunnel or conduit	Rover moves along the wire path and monitors field presence

S.No.	Problem Area	Practical Issue	Project Response
2	Excavation cost	Repair teams may dig unnecessary sections	Encoder feedback gives an approximate distance to the fault
3	Safety risk	Workers may be exposed to live wires or confined spaces	Remote control and video reduce direct entry
4	Manual uncertainty	Basic tools may confirm faults but not physical position	System combines sensing, movement, and distance logging

1.6 Significance of the Study

The study of our project underground wire inspection unit is important as it gives a practical solution for the embedded systems to solve a common problem of inspection. This is the advantage of non-contact sensing as it eliminates direct conductor contact, which enhances safety. In recent years, there has been research on non-contact voltage sensing, which can measure line voltage without contact with the conductor to enhance the installation convenience and safety of the non-contact method[8]. Our project circuit is less complicated than a calibrated voltage sensor, but it has the same general idea of detecting the presence of a field, without making direct electrical contact. Our system is also important as a student level engineering prototype due to the integration of hardware, software and communication in one running system. It serves as a low-cost system for subsequent developments in the field of analyzing and maintaining infrastructure underground, training in utility maintenance, education robotics, and confined space monitoring[9]. Our project is thus of both academic and practical interest.

The importance of this research is also in the aspect of problem-based learning. The project is not theoretical and study, but a practical engineering solution. It involves the use of the concepts of electronics, embedded systems, robotics, communication and programming. Students will be able to learn how real systems are built by wiring up various components and then encountering real-life problems like wiring faults, unstable sensor readings, motor control and communication delay.

The research could also pave the way for future research to enhance low-cost inspection

systems. Further upgrades may include improved sensors, calibration, self logging, cloud storage, autonomous navigation and improved mechanical design. The following are just some of the improvements that the current prototype offers as a starting point. It shows the feasibility of having a small rover which carries a sensing circuit and camera and is able to estimate the distance from a potential wire fault.

1.7 Project Overview

The AWIU is made up of a tracked rover, ESP32 controller, ESP32-CAM, L298N motor driver, encoder motors, non-contact AC voltage detection circuit, battery supply and a mobile application. The rover is controlled wirelessly and travels the route on a wire. The non contact sensing circuit is used to determine if there is an AC field in the vicinity of the wire. The encoder motors are used to aid in determining the rover's distance travelled. You can view live video via the ESP32-CAM, using Wi-Fi. A remote control app enables the operator to remotely operate and monitor the rover.

The system has a step-by-step inspection process. First, the rover is put at the beginning of the wire path. Then, the operator links the mobile app with the ESP32 and opens the stream of the camera. From this point, the rover is then moved along the path. The sensing circuit continually monitors the AC field as the device is moving. When the field is still present, it is assumed that the wire is activated at that point. If the field is removed, the distance is considered as a potential fault location. This process is helpful to the operator in determining the approximate location of the wire break.

1.8 Outcomes to expect

The desired product from this project is a functioning prototype to show the feasibility of underground wire inspection in a controlled environment. The system is supposed to be following a certain inspection route, checking whether or not there is an AC field at that point, and measuring distance based on the feedback from the encoders and output a live video monitoring. The objective of the final result is to demonstrate that low cost embedded components can be used to build an effective inspection support system.

Higher knowledge of the constraints of non-contact sensing and the distance measuring with an encoder. The project will demonstrate the dependence of the response of the

sensor on distance, position of the wire, and the material surrounding the wire. It is also expected to demonstrate the possibility of wheel slip or track movement affecting the encoder distance. These results are significant as they help in defining the limitations of the prototype in practice.

Chapter 2

Literature Review

2.1 Underground Cable Fault Detection

It is a well-known engineering problem to detect faults in underground cables. There is a risk of faults occurring from damage to insulation, mechanical damage, moisture, ageing, overload, poor joints or accidental excavation. Typical approaches to fault location include electrical connection to the cable, and interpretation of the test results, which is challenging. A popular relocation method, time domain reflectometry can detect impedance step changes by analyzing returned pulses from a route along a cable [10]. Time domain reflectometry is a very powerful technique but is not a complete physical inspection solution. It can estimate the distance to the fault point electrically, but in the field a team must determine the distance to the fault point and confirm the exact repair point. In small or low-budget inspection situations, special commercial equipment can be expensive as well. This could provide the opportunity to implement complementary robotic inspection systems to provide a visual and physical distance-based reference. Other methods, such as bridge methods, surge testing and acoustic tracing are also used in cable fault location. These methods can be effective when it is a professional application for utility use but typically don't work in unsafe testing situations and are used by professional personnel.

The most common problem with Cable fault detection is determining the type and location of damage to an electrical conductor. Open circuit fault, short circuit fault, insulation breakdown and earth fault are common faults. Open circuit fault is when there is a break in the conductor and current is not able to flow through the conductor. A short circuit fault is a short low resistance path. Insulation faults are caused by a weakening or damage in the wires protective coating. These faults can be hard to detect in underground wiring installations where the faults are not apparent.

In terms of time domain reflectometry, it is important because it can be used to determine the distance of a fault based on the reflected signals [4]. But this technique is primarily based on electrical characteristics. It will not give real-time visual inspection of the route. Even when an estimate of distance is available, the routing team might have to

go to the site to inspect the route. This process is facilitated by the proposed rover that is moved along the cable path and associates the detected fault condition with the distance travelled.

2.2 Non-Contact Voltage Detection

Non-contact voltage detection involves the detection of electric or electromagnetic fields around an energized conductor. Commercial non-contact voltage testers are usually capacitive couplers or field sensors which detect the presence of AC voltage without encountering the conductor. Experimental research on non-contact voltage sensors has been conducted, and the results have been found to be correct. Electric-field coupling is a method for detecting or estimating the voltage of the line without contacting the measured object, which can improve safety and convenience in the process of working with electricity. Our project does not use a calibrated measurement instrument as a detector, but a simple high gain transistor circuit. The weak field signal from the live wire is drawn into a spiral pickup wire which functions as an antenna. This weak signal is then amplified using three stages of BC547 transistors and is sent to an LED or buzzer. Once the field is lost, the output of the circuit changes and it is possible to record an approximate location of a wire breakage.

The primary benefit of this technique is that it's easy and inexpensive[11]. A major drawback is the sensitivity. This depends on the distance from the wire, insulation thickness, voltage of a line, the direction of an antenna and nearby materials, as well as noise. Our prototype in use, therefore, should be considered more of a field-presence detector for controlled testing purposes and is not a certified voltage measuring device.

The great benefit of non-contact voltage detection is that it requires no stripping, cutting or contact with the conductor. It comes in handy when you cannot or do not want to touch the object. In this project, the sensing circuit is just to sense the presence or absence of the field. Not intended to measure the exact voltage level. This separation is important as it will help maintain the project claim within realism.

The receiving element of the sensing circuit is a spiral pickup wire. This is a pick up wire that is used to pick up the weak magnetic field around the AC conductor. The value of the weak signal is amplified using transistor stages, which can then be used to turn on an output indicator like an LED or buzzer. Once the rover leaves the field of wire,

no longer will the field be detected and the output switches. This change will be used for determining the potential fault.

When developing an ATS, it is essential to take these factors into account. These factors must be considered in the development of an ATS. The inspection system using the robot needs to be stable so as to be able to approach the inspection target with the sensors. The robot may shake, slip or move away from the wire path, making the sensor reading unreliable if the robot shakes too much. Therefore, the mechanical stability becomes an important aspect of this project. Tracked rover design is used to keep the rover in touch with the surface and give it more traction when moving.

The robot should also have an appropriate control system. This project is a wirelessly controlled rover by the operator. This means that when necessary, the user can slow down, stop or reverse the rover. Manual control is beneficial at the prototype level as it provides more control for the operator in the test conditions. In the future, an autonomous control can be added but manual wireless control is more appropriate for the present system.

2.3 Robotic Inspection Systems

ESP32's 2.4 GHz Wi-Fi and Bluetooth combo radio makes it an excellent choice in embedded and Internet of Things prototypes, in addition to its low power microcontroller architecture. In our project, the ESP32 Dev Module will handle the control of the rover, processing the Bluetooth commands, reading the encoder pulses and monitoring the output from the sensors. It is also built-in with the wireless function, which minimizes the need for extra communication modules. The L298N motor driver is used to drive the DC encoder motors. The L298 is a high voltage, high current (2 x 25 A) dual full-bridge driver optimized for inductive loads like relays, solenoids, DC motors and stepper motors, which take standard logic levels for input.

The Android mobile app is controlled through Bluetooth, and camera is streamed via Wi-Fi. Android offers APIs for Bluetooth communication between applications to wirelessly transmit data to other Bluetooth devices, which might be appropriate for short-range rover control. Developed using the modern toolkit of Google for the construction of the native Android user interface, Jetpack Compose[12]. In this application the ESP32-CAM is used as an independent video node to lessen the burden on the main

ESP32 controller. provided a camera driver for the ESP32 series SoC that supports image sensors, with JPEG frame capture workflows. In our project, the camera stream enables the operator to be able to see what is going on in the tunnel and confirm any obstacles that are visible during the inspection.

2.4 Embedded Controllers and Wireless Monitoring

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The ESP32 is used as a central controller as it can give multiple functions in a single system. It transmits control signals and controls motor driver, reads sensor signals and works with encoder pulses. It has integrated wireless capabilities, eliminating the need for additional communication devices [6]. This will make the system small and suitable for a student level prototype.

Video monitoring is done with the ESP32-CAM alone. This separation is beneficial as camera streaming is more complex than merely controlling movement. The ESP32-

CAM is a standalone camera module, which allows the ESP32 to focus on motor control and sensor reading. This facilitates the arrangement of the system and easy debugging.

2.5 Comparison of Related Methods

Table 2.1: Comparison of Cable Fault Detection and Inspection Methods

Method	Strengths	Limitations	Relevance to Project
Time Domain Reflectometry (TDR)	Estimates fault distance from reflected pulse behaviour.	Requires proper cable access and interpretation.	Provides a reference for distance-based fault location.
Surge or Thumper Testing	Useful for identifying certain underground cable faults.	May be unsuitable for delicate or low-voltage systems.	Demonstrates the effectiveness of professional methods but is beyond the scope of this prototype.
Manual Inspection	Simple and direct when the cable is visible.	Unsafe or impractical in tunnels and buried cable routes.	The proposed project reduces the need for direct human inspection.
Non-Contact Voltage Detection	Avoids direct electrical contact and supports quick live-line indication.	Affected by distance, shielding, and environmental noise.	Forms the core sensing principle used in the rover.
Robotic Rover Inspection	Carries sensors and cameras into difficult-to-access spaces.	Requires reliable mobility, power management, and communication.	Represents the primary approach adopted in this project.

As seen in the comparison, each method will have its own pros and cons. The time domain reflectometry method is helpful for determining the distance of fault location,

but it is necessary to have test equipment and technical interpretation [4]. The manual inspection is easy where the wire is visible, but difficult and dangerous in invisible wire. Non-contact voltage detection is more safe but is influenced by the environment [12]. Robotic inspection provides better access, but demands secure and stable motion, communication and power systems.

The proposed project aims to incorporate the beneficial attributes of these methods in a relatively simple design. This won't replace professional cable fault locators, but it will be a helpful aid during inspection. The rover can be moved along the route, the sensor can detect the presence of the field, the distance can be estimated with the help of the encoder, the camera can assist in visual monitoring. This is an ideal system for controlled underground wire inspection.

2.6 Research Gap

While underground electric wires and cables are critical components of a power distribution system, they are still challenging to inspect due to the fact that they are installed in narrow, dark and often unsafe underground locations. Typical inspection techniques rely on manual inspection, external test equipment or fault locators. While these methods can detect some faults, they may not offer continuous visual inspection of the actual condition of the cable within the underground ducts, trenches or conduits.

In view of this, the research gap is that the current systems do not offer a low-cost, compact, stable and sensor-based robot for the inspection of underground wires, which is able to move safely in confined underground spaces and to provide real-time monitoring of cable state[14]. With this in mind, the present study proposes the design and development of an underground wire inspection robot that would assist in performing safe inspection, minimize manual risk, detect visible damage to the cables, monitor the environment and enable early detection of faults in the cables before they reach serious failure.

There is a big gap between professional cable testing instruments and low cost robotic inspection system. Professional tools are precise, but they are costly and might need some expertise in their usage. Expensive and safe, simple non contact voltage testers are usually handheld and do not give a distance measurement. Mobile robots could be able to enter hard to reach areas, but they require a purpose specific sensing system to

be useful for the inspection of wires.

The Autonomous Wire Inspection Unit, on the other hand, is filling this void with the unification of these functions. It's small, inexpensive and can be used in classrooms. It also provides a realistic engineering approach as it does not rely on any one component. Instead it combines sensing, movement and distance estimation with visual monitoring. This will increase the usefulness of the project as a prototype at the end of the third year of engineering.

2.7 Review of Underground Cable Fault Location Techniques

Fault location of underground cables has been based on electrical test instruments, continuity measurement, insulation resistance measurement, bridge method, and time-domain reflectometry for a long time. These methods are helpful when they are applied to professional power networks to estimate cable discontinuities by analyzing the reflected electrical pulses or by analyzing impedance changes. The relevance of the time-domain reflectometry is particularly important because the pulse is pushed into the cable and the reflected pulse is analyzed to determine the position of an open circuit or a short circuit fault. These methods, however, typically require specialized equipment, operators, and direct access to cable terminals. A robotic visual and sensing platform can provide physical traversal along the wire path and associate the detection event with the distance travelled for domestic wiring runs, prototype lines and tunnel demonstration environments, respectively, for smaller conduits.

Our prototype does not aim to substitute the industrial cable fault locators, which are used in high voltage networks. Rather, it focuses on the practical impediment in the field of education and low-cost inspection on the gap where a simple rover can see the path and determine whether the nearby AC field is present or not and report the approximate fault position.

Relevance: The presence of an electric field around an energized conductor means that an energized conductor can be inspected by measuring the electric field, and a non-contact sensor can be used to measure an electric field without breaking through the insulation[15]. Research involving non-contact voltage sensing has also verified the ability to sense voltage despite not physically touching the conductor, which is dependent on distance, geometry, shielding, calibration and surrounding interference. A sim-

plified hardware version of this principle is used in our rover with a spiral pickup wire as an antenna and a transistor amplification chain to send a signal line up to the rover indicating the presence or absence of the field.

It can be compared to contact-based probes, where there is less risk of unintentional contact with live terminals when using non-contact detection. It also imposes design restrictions. However, the signal strength may be weakened with a deep burial, shield, encased in metal conduit or near other energized conductors. Our prototype is only suited to the inspection of a single wire in a non-metallic conduct or in a tunnel-like structure. This restriction not only gives a more uniform field pattern to the sensing antenna but also allows the system to have a greater degree of confidence in recognizing the disappearance of the field as indicative of a possible breakage.

The utility of fault location techniques is that they help to save time needed to locate the faulted section of a cable. But there are a number of electrical methods that operate from a cable terminal instead of the actual route. This implies that they estimate the position of the fault indirectly. In actual repairs, the distance still needs to be matched with the actual cable layout, which is an estimated distance. This matching process can be a problem if there are curves or concealed parts at the route.

The proposed rover is a more direct method of physically inspecting. It follows the wire through the field and verifies the field while moving. This indicates that the fault indication detected is associated with the position of the rover. The measurement is only approximate, but can assist the operator in deciding on the area to be tested further.

2.8 Literature on Robotic Mobility for Confined Inspection

The ability to use mobile robots for inspection tasks makes it unique because it can access environments that are otherwise impractical for human inspection for safety, convenience or time reasons. Robotic inspection is particularly useful in small, dark, dusty and potentially electrified spaces. Movement is not the only major engineering need; it's also stable sensing. The rover should not get too far away from the line of the target, should not lose balance, grip, or control of its movement, and should be moving at a consistent pace. According to Springer Handbook of Robotics, the design of a mobile robot is typically the combination of locomotion, sensing, control, power, communication and environment constraints[16]. This principle clearly applies to our proposed

inspection unit. Tracked motion was chosen because the prototype requires to be gripped and stable in a tunnel-like route. A tracked chassis is spread over a wider area than small wheels are and decreases the likelihood of slipping off rough test surfaces.

The drawback is that tracked platforms could require more power and cause more mechanical friction. Stability is more important than the maximum speed in our project because the rover will be used to inspect and not to travel at high speeds. Encoder motors are a convenient way to measure distance when inspecting. As the wheel rotates, the encoder produces pulses, and the controller transforms the number of pulses into distance travelled by the wheel based on the diameter of the wheel and the number of pulses per revolution. The major drawback is that wheel slip, friction of the surface and turning can cause inaccuracy.

The project has to meet one of its most critical design needs, the mobility. The rover has to be able to move very smoothly so as not to disturb the wire path from the sensor. If the movement is unstable, it is possible that the detector will lose the field even if the wire is not broken. This might result in a false fault indication. Hence, careful consideration must be given to the mechanical design, track grip and position of the sensors.

The encoder system plays an important role on mobility as well. The encoder provides feedback in the form of pulses as the motor is turned. These pulses can be used by the controller to approximate distance. This approach is based on the premise that motor rotation is directly proportional to rover motion, however. If the track slips, there may be a possibility that the motor spins without the rover driving the same distance. That's why the project specifies that the fault location is "approximate".

2.9 Review of Wireless Control and Monitoring in Embedded Systems

Wireless control may be important as the operator may have to stay outside the unsafe or inaccessible space for tunnel inspection. The ESP32 platform can be used in educational robotic systems due to its integration of the Wi-Fi and Bluetooth modules, decreasing the need for additional communication modules and reducing space. In our project, Bluetooth will be deployed for control of the movement. Telemetry and the Wi-Fi will be utilized by the ESP32 CAM for streaming of the video. This separation reduces conflict in the processing of motor commands and camera data, which reduces

bandwidth use.

The live feedback of the visual elements is done separately with Wi-Fi video streaming due to the higher data throughput needed for the live feedback compared to the commands for movement. The use of the ESP32-CAM in our project gives the operator visual awareness of the condition in the tunnel and rover movement, which is an often-used camera platform in embedded imaging prototypes, and is used in the our project to make the system as affordable as possible[17]. In our system, the camera stream is not used for computer vision. Rather, it's serving as a surveillance and confirmation device.

The system is wirelessly controlled, creating a safer and more convenient system. The operator can not be required to stand by the rover during the inspection. Instead, the commands for moving can be sent remotely via the mobile application. This aligns with the primary objective of the project since the rover will be used in places where humans might not be able to reach.

Additionally, wireless monitoring enhances the user experience. The camera stream enables the operator to see the inspection path, the rover's location and detect the existing obstacles. If no video monitoring, the operator would only have sensor and distance readings. The operator now has a camera record the entire inspection process and would be able to make better decisions based on the recordings. For this reason, the ESP32-CAM is crucial to the system [5].

2.10 Summary of Literature Review

The literature reviewed indicated that an Integrated inspection system is required. Based on the cable fault location method, the results presented in [4] indicate that fault distance is important. It is demonstrated via non-contact sensing that electrical field detection is a way to enhance safety [12]. Robotic inspection has been demonstrated to be a means of supporting inspection in challenging environments, using mobile platforms [10]. These functions can be implemented in a small prototype with the embedded controllers like the ESP32 [6].

The integration is the main contribution of this project. It's not just a rover, it's not just a sensor, it's not just a camera. It integrates three of them into an interactive unit. This is significant since most real inspection problems will involve more than one function.

It is important for a repair team to be aware if a fault exists, where it can occur and what the inspection path is. In a controlled prototype solution the needs are met by the Autonomous Wire Inspection Unit.

There are many reports in the literature that there is a need for a safe, low cost and practical inspection system for concealed wiring environments. Industrial fault location techniques are accurate but may require special equipment and access to terminals. Non-contact voltage sensing minimizes contact dangers but is susceptible to environmental and geometric influences. Mobile robots can use sensors to access hard-to-reach areas for inspection and embedded wireless systems can enable the operator to control the rover and get feedback from it remotely. The results support the design of AWIU as an integrated prototype that brings together: robotic mobility, AC field sensing, distance estimation, live video and mobile control.

The review results revealed that reliable methods used for cable fault location have been available, but they tend to be expensive, instrument-dependent and may not be usable for in-field physical inspection in narrow [18]. Also demonstrates that using non-contact field sensing is safer than direct conductor contact, but simple field detectors are typically not used for physical movement or distance logging. Our project tackles the research gap between a mobile rover, a field detector, live video streaming, wireless control, and encoder-based distance sensing into a low-cost prototype of an inspection rover.

Chapter 3

Design & Methodology

3.1 System Overview

The system overview of our project Autonomous wire inspection unit. Includes a tracked rover that has an ESP32 Dev Module, an ESP32-CAM, an L298N motor driver, encoder motors, a battery supply, and a non-contact AC voltage detection circuit. The rover is operated via a mobile app using Bluetooth, and the ESP32-CAM sends live videos through Wi-Fi. The system is designed in a way that motor control and video tasks are separate, allowing movement to stay responsive while the video stream works on its own. When the rover is turned on, the controller starts up all the connected parts.

The operator then connects the mobile app through Bluetooth and starts the live video feed using Wi-Fi. The rover moves along the inspection path. As it moves, the encoders track the wheel rotation, and the voltage detector checks the area around the wire. If the voltage signal is lost, the system records the distance from the encoder and notifies operator.

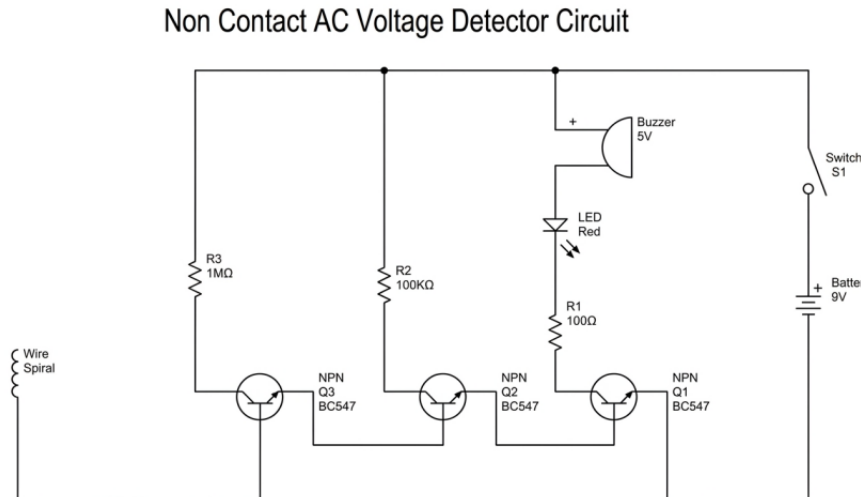


Fig. 3.1: Non-Contact AC Voltage Detector Circuit

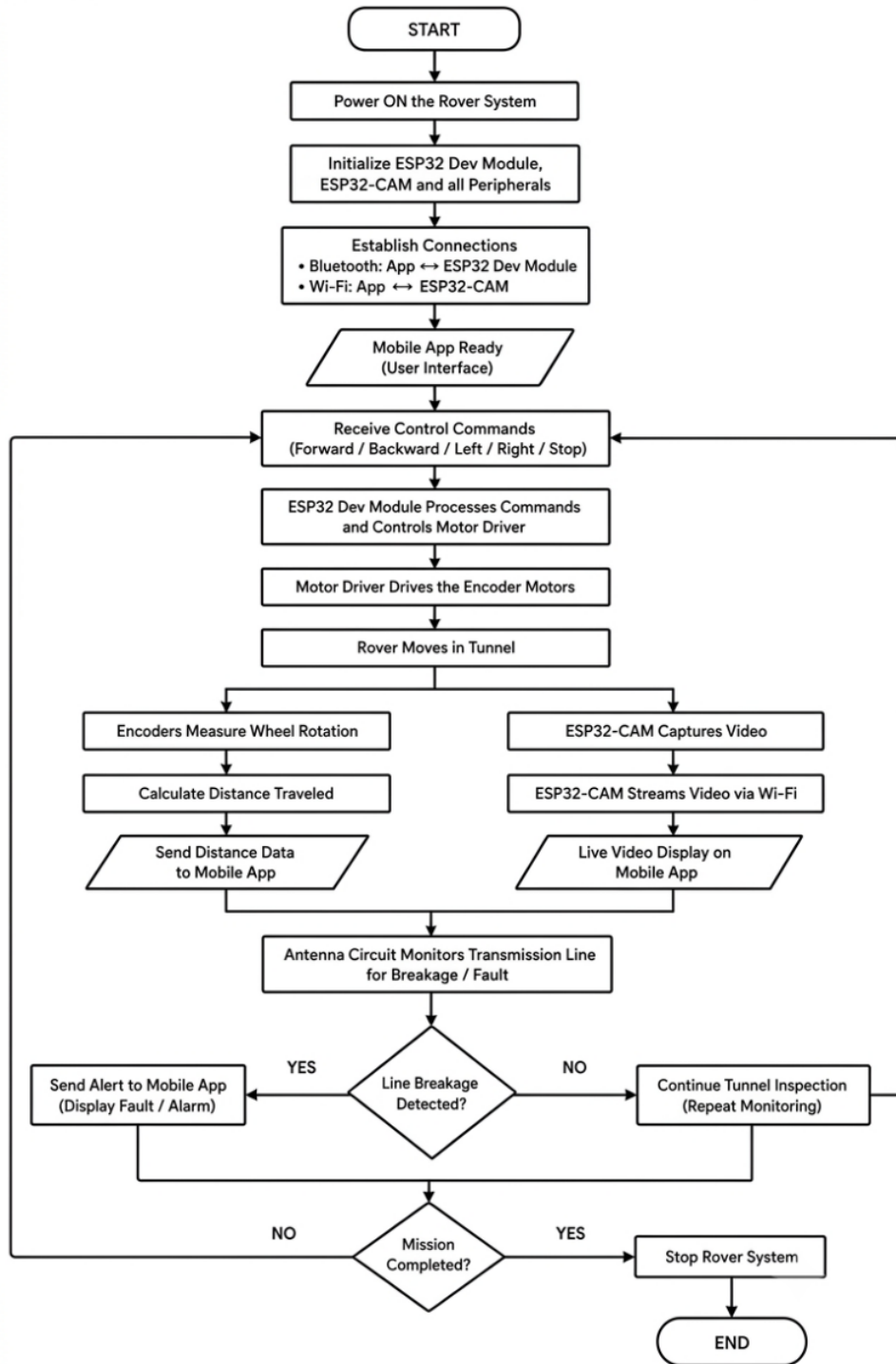


Fig. 3.2: Operational flowchart of the Autonomous Wire Inspection Unit

3.2 Hardware Methodology

The hardware of our project is the way about selecting low cost, compatible hardware which will be able to fit on a small rover. The main thing is the ESP32 Dev Module. Gives orders to a Bluetooth device, regulates the motors, counts the pulse from the encoders and monitors the voltage levels.

The live monitoring is done by using the ESP32-CAM module. It captures the videos and transmits the video frames via wireless fidelity (Wi-Fi). The camera is not directly connected to ESP32 main unit to eliminate any interference of video processing with the motor control and reading of the encoder. This configuration will ensure more reliable operation of the system and easier testing. JGA25-370 encoder motors are used for the rover's movement. Each motor has an encoder which generates pulses when the motor rotates. The ESP32 is counting these pulses and is used to calculate the distance travelled. This is accomplished through the wheel size, and number of pulses per full turn.

$$\text{Distance} = \frac{N \times \pi D}{P} \quad (3.1)$$

This formula is used to calculate the distance that the rover has traveled from its base. However, due to issues such as wheel slippage, surface conditions and mechanical accuracy, the actual distance may vary, so it is important to calibrate the system before use in the field. The motor control circuit is centered around an L298N motor driver IC which controls the motors. The L298 is a dual full-bridge driver which can be used for inductive loads (DC/Stepper motors). Accepts the signals from a controller in the form of standard logic signals. In our project, these are sent from the ESP32 to the motor driver that then sends the proper current to the motors to move forward, backward, turn left, turn right or stop.

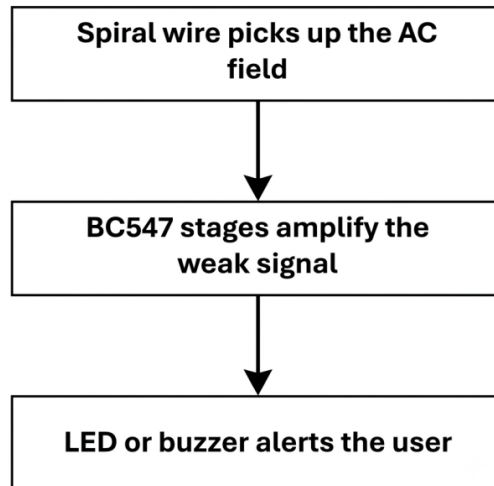


Fig. 3.3: Non-contact AC voltage Flow Diagram

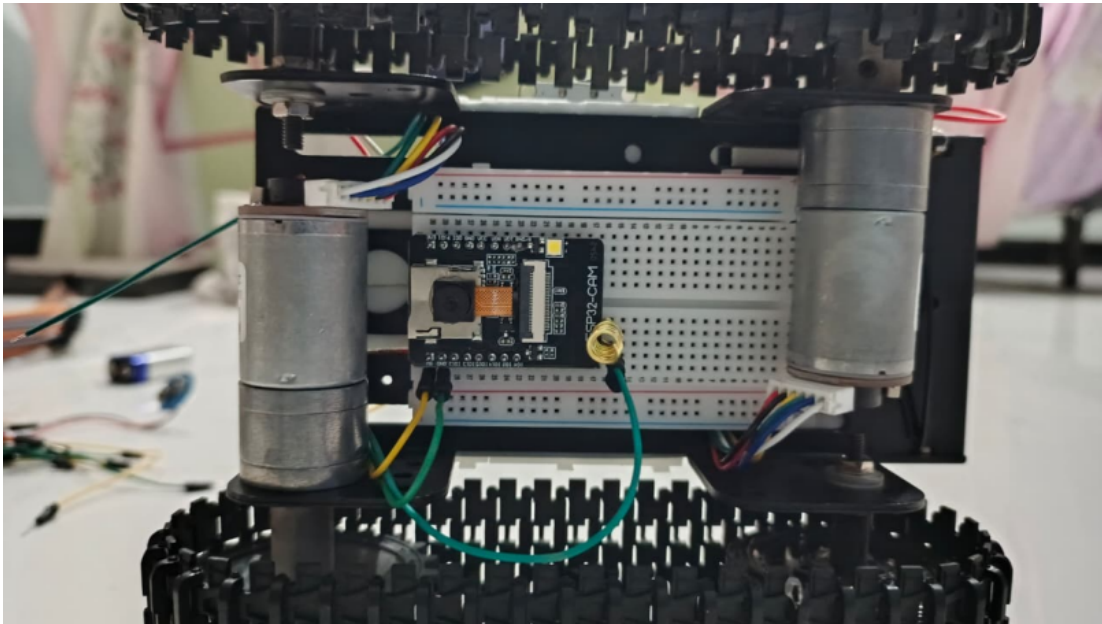


Fig. 3.4: Tracked rover chassis and integrated prototype with ESP camera

Table 3.1: Hardware Components Used in the Project

Component	Function	Reason for Selection
ESP32 Dev Module	Main controller for motors, encoders, Bluetooth, and sensor logic	Integrated wireless features and sufficient GPIO pins.

ESP32-CAM	Live video streaming over Wi-Fi	Low-cost camera module for remote observation.
L298N Motor Driver	Controls DC encoder motors	Suitable for dual DC motor direction and speed control.
JGA25-370 Encoder Motors	Rover movement and distance feedback	Provides pulse data for distance estimation.
Tracked Chassis	Mechanical movement platform	Stable movement and provides sufficient mounting space.
Spiral Antenna Circuit	Detects AC field presence	Enables non-contact live wire sensing.
LED and Buzzer	Fault and voltage indication	Provides simple visual and audible feedback.
Battery Supply	Powers electronics and motors	Supports portable and independent operation.

3.2.1 Detailed Hardware Components, Purpose and Working

This section describes the various hardware modules that are used in the Autonomous Wire Inspection Unit and relates each to its actual function in the working prototype. The hardware was chosen to ensure the system was low-cost, compact and could be readily demonstrated in a laboratory tunnel or conduct setup. The design of the core consists of the control module, movement module, sensing module, video monitoring module, power module and operator feedback module.

The main controller of rover is the ESP32 Dev Module. It handles the movement instructions from the mobile application via Bluetooth, controls the motor driver pins, detects the pulses from the encoder and monitors the output of the detector. The ESP32 was used for its support for wireless connectivity and the availability of a variety of digital input/output pins, making it ideal for small, embedded control applications [6].

The ESP32-CAM module is used stand-alone as a video unit. It captures the inspection view from the rover and streams it over Wi-Fi, allowing the operator to observe the tunnel path, the wire position, and any visible obstacles. Keeping the camera module separate from the main control ESP32 reduces the processing load on the movement

controller and improves system stability during testing. The ESP32-CAM development board supports camera interfacing and compact embedded operation.

The L298N motor driver acts as the power interface between the ESP32 and the DC encoder motors. The ESP32 cannot directly supply the current required by the motors, so the motor driver receives low-current logic signals and switches the motor supply according to the required direction. The L298 is designed as a high-voltage, high-current dual full-bridge driver for inductive loads such as DC motors and stepper motors [11].



Fig. 3.5: Hardware Components

The JGA25-370 encoder motors are used to control movement and provide information about how far the rover has moved. Each motor turns the tracked rover and sends out electrical signals, called pulses, as the wheels move. These pulses are counted by the ESP32, and by using the wheel size and the number of pulses per full rotation, the system calculates the distance covered. Gear motors are good for our project because the gears change the motor's fast spinning into slower, stronger movement, which is better for a small, tracked rover.

It is based on a spiral wire that is like an antenna and senses the electric field that is created around an active AC wire. Three stages of BC547 transistors amplify the weak signal that it receives. Then it is indicated by an LED and a buzzer whether the field is there. In the system, if the field is lost, it is considered a possible break in the wire and, the current distance from the encoder is stored to monitor the rover's position. The BC547 is a widely used NPN transistor that can be used in circuits where low power switching and amplification are required. The prototype hardware and interface images shown in the project presentation (Figure 3.6) clearly demonstrate that the two are interconnected.

The rover has all the motor drivers, batteries, sensing circuit, ESP32 electronics and camera set-up on a small chassis. The mobile user interface allows the operator to control the movement, receive a live status update and receive assistance for visual inspection..

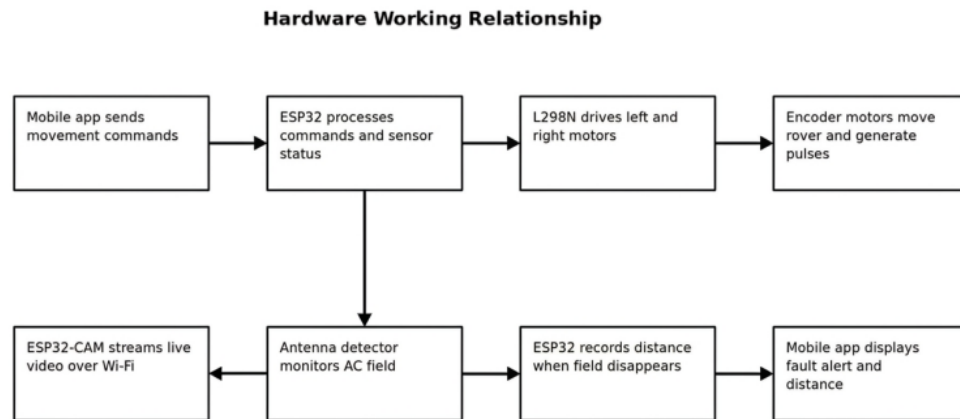


Fig. 3.6: Working relationship between hardware modules

The first part of the Hardware setup is the mobile app. The command is sent using Bluetooth and received by the ESP32 Dev Module. The ESP32 then activates the appropriate pins of L298N making the encoder motors drive the rover forward, backward, left, right, or stop. The system is continually monitoring the encoder feedback whilst the rover is in motion to ensure that it can detect any problems and monitor the distance traveled. Meanwhile, the ESP32-CAM is transmitting a third video stream via Wi-Fi. This allows the operator to view the rover's location as it happens. Sensing path is simultaneous to the movement. Antenna circuit is used to test the electromagnetic field surrounding the live wire. The system will assume that there may be a line break if the field is lost and the previous distance reading is used to aid in problem location.

Table 3.2: Detailed Purpose of Major Hardware Modules

Hardware Module	Purpose in the Prototype	Working Contribution
ESP32 Dev Module	Main controller for rover movement and fault logic	Receives Bluetooth commands, controls motor-driver pins, reads encoder pulses, and checks detector status.

Hardware Module	Purpose in the Prototype	Working Contribution
ESP32-CAM	Live inspection camera	Streams tunnel or conduit views over Wi-Fi so the operator can monitor the physical inspection path.
L298N Motor Driver	Motor power interface	Converts ESP32 logic-level commands into motor direction and drive signals for the left and right motors.
JGA25-370 Encoder Motors	Movement and distance feedback	Move the tracked rover and generate pulses used to calculate the approximate travelled distance.
Spiral Antenna and BC547 Circuit	Non-contact voltage detection	Senses the AC field near a live wire and amplifies the weak signal to activate LED and buzzer indications.
Battery and Switch	Portable power supply and isolation	Provides independent rover power and allows the prototype to be safely turned on or off during testing.
Tracked Chassis	Mechanical platform	Supports all electronics and provides stable movement over the simulated tunnel or pipe path.

3.3 Non-Contact Detection Circuit

The non-contact AC voltage detection circuit consists of a spiral pickup wire, three BC547 NPN transistors, resistors, an LED and a buzzer, a power switch and a 9V battery. The spiral shaped wire is also an antenna. The weak signal is produced due to the electric field around the wire, when it approaches an energized wire. This is then amplified by the transistor stages. The output indicators are controlled by the last transistor. If there is a voltage detected, the LED will light up and the buzzer will sound. When the rover enters an area where the field is not anymore, the LED and buzzer are not activated

anymore, and the controller thinks that this could be a possible break. A fault is then indicated on the mobile app, and the distance of the encoder is used to approximate the location of the fault. This method is based on the principle of non-contact voltage detection, which involves sensing the voltage by means of the electric field, without making direct contact with the conductor [12].

3.4 Software Methodology

The software system of our project Autonomous wire inspection unit consists of rover firmware and camera firmware as well as an application for the Android mobile. The rover code is coded in the C++ programming language in an Arduino-like style for the ESP32. It configures the motor pins, Bluetooth communications, interrupts from the encoder and detector input. The computer program (firmware) continuously scans for commands and moves the motors as needed. Kotlin is very popular for developing Android applications, while Jetpack Compose is used to build modern and declarative interfaces for Android screens. This app features a stop button, a speed adjustment feature, a distance display, a real-time camera view, and information on any faults. To send movement commands, Bluetooth Classic Serial Port Profile (SPP) was used as a simple method for sending commands between the phone and the ESP32 rover. Android Bluetooth APIs allow applications to discover, pair, connect with and communicate with other Bluetooth devices. The ESP32-CAM uses Wi-Fi to transmit video as the movement commands need less bandwidth than video. The tools and technologies used for software development are listed in Table 3.3.

Table 3.3: Tools and Technologies for Software Development

Layer	Technology	Purpose
Android Application	Kotlin	Application logic, state handling, Bluetooth commands, and dashboard control.
Android UI	Jetpack Compose	Declarative user interface with cards, buttons, status indicators, and camera view.
Rover Firmware	Arduino C++ for ESP32	Bluetooth communication, motor control, encoder reading, and detector monitoring.

Layer	Technology	Purpose
Camera Firmware	ESP32 Camera Web Server Approach	Wi-Fi video streaming and remote visual monitoring.
Communication	Bluetooth Classic and Wi-Fi HTTP	Movement control, telemetry exchange, and camera monitoring.
Development Tools	Android Studio and Arduino IDE	Mobile application development, firmware programming, debugging, and testing.

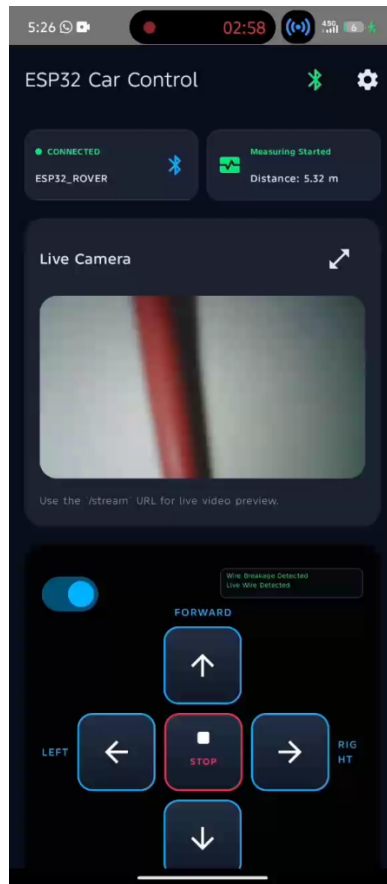


Fig. 3.7: Mobile application architecture and interface

3.5 Communication Protocol

The system is very simple and involves only text commands to be sent from the mobile application to the ESP32 rover. Each command is sent as a short character/string. This method ensures easy debugging via the serial monitor and easy processing on the

microcontroller. The camera stream is managed in its own ESP32-CAM Wi-Fi server.

Table 3.4: Bluetooth Command and Telemetry Protocol

Command or Message	Direction	Function
F	App to Rover	Move forward while command is active.
B	App to Rover	Move backward.
L	App to Rover	Turn left.
R	App to Rover	Turn right.
S	App to Rover	Stop motors.
V###	App to Rover	Set motor PWM speed value.
M1 / M0	App to Rover	Start or stop measuring mode.
R0	App to Rover	Reset distance counter.
DIST:<meters>	Rover to App	Send measured travel distance.
FAULT	Rover to App	Report probable breakage event.

3.6 Operational Workflow

The operational flow of our project is as follows:

- Turn rover system on.
- Power on the ESP32 Dev Module, ESP32-CAM and any peripherals.
- Connect mobile App with ESP32 Dev Module using Bluetooth.
- Set up Wi-Fi connection between the Mobile Application and ESP32-CAM.
- Get instructions for moving from the mobile app.
- Run command on ESP32 and command Motor driver.
- Explain how to make the rover go through the tunnel shaped path.
- Count the pulses from an encoder and work out the distance travelled.
- Stream and take live videos with the ESP32-CAM.

- Using the antenna circuit to monitor the transmission line.
- Send breakage fault alert and distance if breakage is detected.
- If no breakage is found, then continue inspection to complete mission.

3.7 Testing Methodology

The testing methodology of our project is to guarantee the correct, consistent and safe functioning of the Autonomous Wire Inspection Unit in different circumstances, the testing process was designed. The testing process was broken down into various phases to test each component, followed by the actual system. Firstly, unit testing has been done to test the individual functioning of the hardware and software components such as microcontroller, sensors, motors and communication components. This allowed for confirmation of the correct functionality of each part and helped to find out if any problems occurred early on, which could have an impact on how the system functions. This was followed by integration and field testing to test the integrated system under conditions of simulated use.

Integration testing validated all the hardware and software components and field testing were conducted using a controlled tunnel environment for the rover to experience wire problems, traverse the inspection route and to perform accurate distance and video results. Much focus was placed on consistency, the system's capacity to deal with problems and demonstration of the system's performance. All the results were carefully noted and studied. An organized approach ensured that the inspection unit could perform all the necessary functions, safety requirements and reliability objectives for use in underground areas.

3.8 Detailed Mechanical Design Considerations

The mechanical design of our project Autonomous Wire Inspection Unit is developed with three main considerations: movement stability, sufficient space for components and safe placement of sensors. It is not a conventional two-wheel type chassis; it is based on tracked chassis to provide greater contact area and to maintain steadiness of the unit when travelling along a tunnel-type test path. The chassis has width of approximately 7 inches and length of around 6.5 inches which is adequate to accommodate the ESP32

controller, motor driver, camera module, batteries and the non-contact sensing circuit.

The front section of the rover is particularly significant as the spiral pickup antenna must be near the wire to be tested.

If the sensor is at a distance from the wire and/or too high, the electric field signal may be too weak and unreliable. If it's too low or not fastened properly it might be able to reach the ground or shift when the rover moves. As a result, its location is vital and integral to the design and must be painstakingly set up rather than simply added to the system. The decision was made to select a chassis instead of a completely enclosed industrial chassis as an educational platform.

This option will facilitate construction, possible replacement of parts and test circuit access. If it were for an industrial application, the electronics should be protected from dust, water and shocks and strain relief for cables.

3.9 Electronic Circuit Design and Signal Flow

In our project the principle behind the voltage detection circuit is that a live AC wire has an electric field around it. A signal from this field is picked up by the spiral pickup wire. The signal is too weak to directly trigger an output device, so it receives three levels of amplification from BC547 transistors. The last stage is for the LED and buzzer. This setup is based on the general method of non-contact electric field sensing, in which the non-contact sensor collects the field data without contacting the wire.

The three-stage amplification is needed because the signal the pickup antenna receives is weak. The first stage amplifies this poor input signal, the second stage amplifies it again and the third stage is powerful enough to enable the LED to illuminate and the buzzer to sound. When the wire is intact, the field is present and it is indicated by illuminated green LED in the prototype. When the field is not present the LED changes and the system indicates that a possible break exists. An additional warning to the operator is provided by the buzzer.

This separation allows us to avoid problems such as noises from the motor or resetting of the controller affecting the detector. But, for later versions, it is better to use regulated power, filtering capacitors and common grounding as necessary. The current design is suitable for demonstration purposes but will require enhancements for harsh

environments.

3.10 ESP32 Control Logic

In our project the main controller to control movement, command interpretation, counting the encoders and sensing is the ESP32 Dev Module. It is controlled via Bluetooth with the mobile app. All the instructions to the rover are given in these commands. For instance, 'F' will move forward, 'B' will move it backward, 'L' will turn left, 'R' will turn right and 'S' will stop the motors. Commands ending with a "\n" are easier to process and easier to debug over serial communication since they are simple. L298N motor driver is controlled by the ESP32's GPIO signals. The L298N is a motor driver which can drive DC motors and STEPPER motors. In the rover it is used as an interface between the lower powered control pins and higher-powered motor pins. The ESP32 will tell the driver which motor(s) to spin and how fast, and the driver will deliver the power to the motor(s). The controller keeps tally of the pulses made by the encoders as the rover rolls.

Each pulse corresponds to a small turn of wheel. The distance is determined by the number of pulses, the circumference of the wheel and the number of pulses for a complete revolution of the wheel. This approach works great for straight moves, but in real world, there may be some errors in the distance between wheel due to wheel slip, uneven surface or turning. For this reason, it is important to compare the actual distance measured with the calculated distance, to be able to estimate any errors.

3.11 Mobile Application Design Methodology

The mobile application was developed as an easy-to-use operator dashboard, rather than a full enterprise application. It is used for transmitting movement instructions, displaying distance updates, visualizing the connection status and transmitting live camera video. The selection of Kotlin and Jetpack Compose is due to Compose being easier to create dynamic UI elements, such as buttons, cards, sliders, and status indicators. The user controls are done by pressing the moving buttons. When the button is pressed the rover will move, when the button is released, the rover will stop. This is to minimize the chance of the rover being in motion when the user releases the button. The prototype is further made safe with an emergency stop function.

3.12 Camera Streaming and Operator Visibility

The ESP32-CAM can transmit live video via Wi-Fi. The camera is for better visibility in the inspection of tunnels. This enables the operator to view the path, to identify obstacles, and to ensure that rover is in-line with the wire route. In this version, the camera is not used to automatically detect fault. By separating the fault detection task from the video processing task, it is possible to reduce the computational load of the task and focus on the system to be able to sense the electrical field.

There are two ESP32 modules to handle video streaming and motor control. The ESP32-CAM is used to handle the video stream and the main ESP32 is used for Bluetooth commands, motor control, counting the number of rotations of the encoders and reading sensor data. This division helps to lessen the burden on one microcontroller and make the design clearer as the motor systems can now be tested without the camera and vice versa.

3.13 Data Handling and Fault Logging

The most critical information that our system gives is the distance travelled by the rover when a potential fault is identified. This distance from the rover is sent to the app and displayed to the rover operator. The approximate location of the fault is taken to be the distance at which the detector can detect that the field is lost.

For the current version, the data is shown only on the mobile-app. In the future, it can be recorded in a local database or the cloud with the event, time, distance, video snapshot and operator notes. Our project already mentioned that cloud or firebase integration would be a great improvement. This would be beneficial for the maintenance crew to be able to check the inspection records when the rover is removed from the tunnel.

3.14 Safety and Operational Assumptions

In this project Autonomous wire inspection unit, the system was created to be a didactic prototype for low-risk tests. It should not be directly linked to unsafe high voltage systems without the proper isolation, supervision and certification. The non-contact detector is designed to detect the magnetic field of an energized wire and is not a safety

rated voltage detector. This is important because it means that electrical work done in a safety critical situation must be carried out with the correct tools and trained electricians. It is assumed that the tunnel environment has one wire or a controlled test line in a non-metallic conduit.

Determination of the presence can be made less reliable in the presence of metallic conduits, heavy shielding, bundled cables and strong surrounding electric fields. Our system also assumes that the rover can freely operate on the inspection path and is not stuck. These assumptions determine the limits of operation of the prototype and help avoid making unrealistic claims regarding its performance.

3.15 Sensor Positioning and Mounting Arrangement

The non-contact voltage sensing circuit is very sensitive to the location due to the fact that it relies on the electric field around the live conductor. When the spiral pickup antenna is farther away from the wire, the field might not be detected correctly. If it is too near or not securely mounted, vibrations from rover movement can impact the reading. Thus, sensors must be mounted in a forward stable mount on the rover frame. The antenna for this project is considered as the initial sensing point of the rover. It should be oriented towards the anticipated wire path before the main body of the rover is in that position. This facilitates the system to identify a change in the field condition at the appropriate location during inspection. The antenna should also be kept clear of motor wires, motor driver and cables which can cause unwanted electrical noise. A small plastic or acrylic support can be employed to keep the antenna in place while keeping electrical safety (Figure 3.8).

3.16 Power Management and Distribution

APCI power management supports the Autonomous Wire Inspection Unit motors, controller, camera and sensing circuit. The motors have to be larger as they are used to move the tracked chassis. ESP32, ESP32-CAM and the sensing circuit should be powered by a stable power supply for proper functioning. These issues could occur if the voltage is lower when the rover is moving, making the rover move slower or causing the Bluetooth connection to become unstable, or causing the camera stream to drop out.

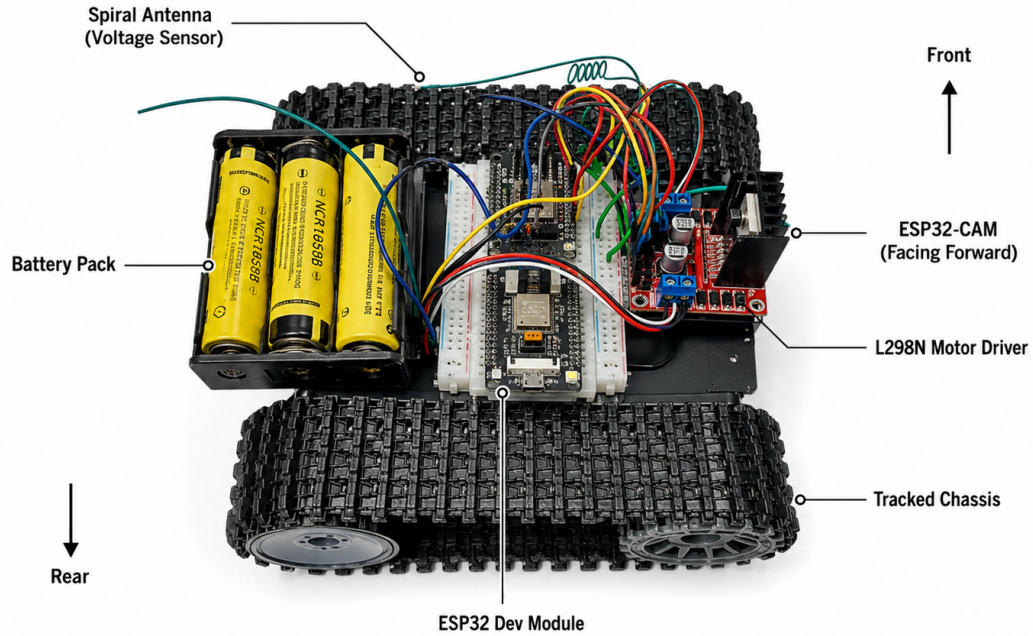


Fig. 3.8: Sensor Placement on Rover Chassis

The design isolates the high current movement section from the low current control and sensing section, to minimise these issues. The motor load is controlled by the L298N motor driver and the ESP32 controls the logic signals. All components of the circuit (ESP32, motor driver, sensing circuit) must share a common ground to receive the signals correctly. The battery voltage should be checked before each test, as poor battery performance may impact moveability, sensor response and communication reliability.

3.17 Mechanical Stability of the Tracked Rover

The tracked chassis was chosen as a desirable solution as it allows a better surface contact and balance than a simple two-wheel structure. The rover will have to navigate a path that is a tunnel, in which case it is important that the rover traversed this path slowly and steadily so that the sensor reading is consistent with the distance from the wire. The field might get lost by the rover and cause the detector to display a wrong fault indication if the rover shakes or moves away from the wire path.

The mechanical design should also allow for the placement of the camera module, sensing circuit, motor driver, and battery as well as the control board. The weight should be placed evenly so as not to tilt the rover when moving it. The rover could pull in one

direction if the battery is positioned too far to one side. A well-balanced design will yield better movement accuracy and the encoder distance measurement will be more precise.

3.18 Signal Flow Between Subsystems

Correct signal flow between the hardware modules is crucial to the working of the system. The ESP32 receives movement command via the mobile application through the Bluetooth. These commands are sent to the ESP32, which executes them and sends logic signals to the motor driver (L298N). Then the motor driver is responsible for the direction and motion of the encoder motors.

Meanwhile, the encoder motors pulse back data to the ESP32, which can be used to calculate the distance. The non-contact voltage detector is used as a sensing input. If the detector detects the AC field, the ESP32 considers the part of the wire as active. If the field is lost the ESP32 stores the current distance as a possible fault location. The ESP32-CAM is operated independently via Wi-Fi and transmits the video to the operator. They maintain sensing, distance control, and video monitoring while keeping them from being tied up with the movement control on one module (Figure 3.9).

3.19 Distance Measurement Method

Distance measurement method is based on counting of encoder pulses. The encoder mounted on the motor produces pulses when the rover is moving. The ESP32 counts these pulses and calculates the distance by multiplying the wheel size with the number of pulses counted, based on the encoder pulse count. This distance is used to determine the approximate location of the fault from the starting point.

The actual distance traveled measured by the rover is not likely to be perfectly accurate as the rover uses tracks and track movement may be influenced by slip-on tracks, turning, loading of the tracks, and surface friction. The system therefore does not provide an industrial grade fault distance measurement, but rather an approximation. This can still be helpful as it will help to reduce the area of the inspection and provide the operator with a real location reference.

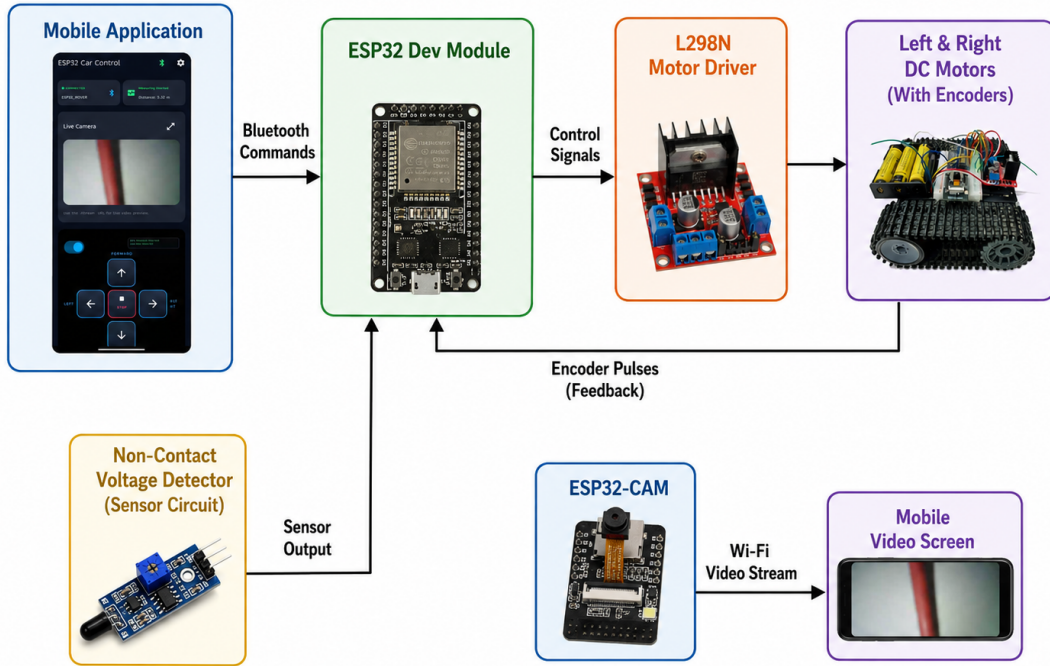


Fig. 3.9: Complete Signal Flow Diagram of the System

3.20 Sensor Calibration Method

The non-contact detection circuit is sensitive to distance, wire position, voltage level and objects in the vicinity and requires calibration prior to final testing. The first step is to position the antenna close to a live wire and check that the LED or buzzer lights up/buzzes. The second step is to slowly pull the antenna away from the wire and note the distance where the response is reduced or goes away.

The process can be used to determine the useful detection range of the sensor. After mounting the sensor on the rover, the same calibration should be repeated as the final position of the antenna can influence the reading. Calibration will also minimize false detection. The stable sensor response implies good ability to detect the true value of loss in the field rather than noise or movement error.

3.21 Software Logic for Fault Detection

The software logic is straightforward and decision making process is simple. The first thing the ESP32 does is determine if the rover is receiving commands to move. It then

reads encoder pulses and increments the travelled distance. Meanwhile, it is measuring the output of the non-contact voltage detector. If the detector output indicates that there is a field present, the rover proceeds to inspect. If the field is not found, the distance saved is the closest possible fault location.

This logic works well for the current prototype as the project will be a single inspection path with a single wire. This software does not guarantee to detect all cable faults. It only marks an approximate location of a possible wire breakage where the electric field no longer is detected. This allows the system to be realistic and for demonstration purposes in any academic setting.

3.22 Mobile Application Functional Design

The rover's operator interface is through the mobile application. It enables the rover to move forward, backward, left and right by the user. It also has a stop command to ensure safety and to provide more control. The app shows the sensor status and distance information, allowing the operator to monitor the sensors inspection progress.

The design of the app needs to be simple, because the operator may have to operate the rover and watch the video simultaneously. A complex interface could lead to higher rate of user mistakes. On the main screen, there should be an indication of the distance travelled, movement buttons, wire status and a fault alert. When the field is lost, the following warning should be visible in the app: Possible Fault Detected, with the approximate distance (Figure 3.10).

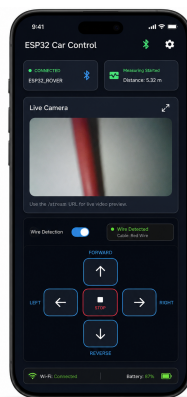


Fig. 3.10: Mobile Application Interface Layout

3.23 Testing Plan Before Integration

Each of the subsystems must be tested individually before the entire system is implemented. The motor control system should be tested first to see if the rover is able to move in all directions. The encoder system should then be tested to ensure that the pulses are being received properly. The sensing circuit should be tested close to a live wire to ensure that it can detect the field. The ESP32-CAM needs also to be tested to ensure that the video stream is visible on the mobile device.

These tests are followed by the linkage of the subsystems. This is a gradual process which makes troubleshooting easier. Each subsystem has already been tested and if the complete rover fails in final testing the project team can easily determine the problem. This approach also enhances the confidence in the prototype.

3.24 Design Limitations Considered During Methodology

There are some limitations in the prototype that are taken care of in the methodology. The system is not designed for use at high voltage in industry. It is intended for controlled testing purposes, academic demonstration and models for low risk inspections. The sensor is also not a calibrated voltage measuring equipment. It only tests on the presence or absence of a field.

For short range testing, Bluetooth and Wi-Fi are appropriate, but may not provide consistent performance in long tunnels and/or in environments with significant obstructions. Track slip can also impact encoder distance measurement. Such restrictions are recognized as the project is not intended to produce a certified industrial product, but rather, to test and validate the work concept.

Chapter 4

Results and Discussion

4.1 Prototype Implementation

The prototype was developed by mounting the ESP32 Dev Module, motor driver, Encoder motors, ESP32-CAM, battery system and non-contact voltage detector circuit on a tracked rover chassis. The controller and motor driver were re-positioned to allow for easier wiring, and the sensing antenna was mounted forward into the rover for better readings closer to the wire path. The movement of the rover and all aspects were controlled by the mobile app, which had only one spot for this control. The user was able to move the rover forward, reverse, to the left or right, stop the rover and view the distance measurements and live camera footage. This combination in one place made it easier to use as the operator wouldn't need to use other tools to move the rover, view the video and check the distance.

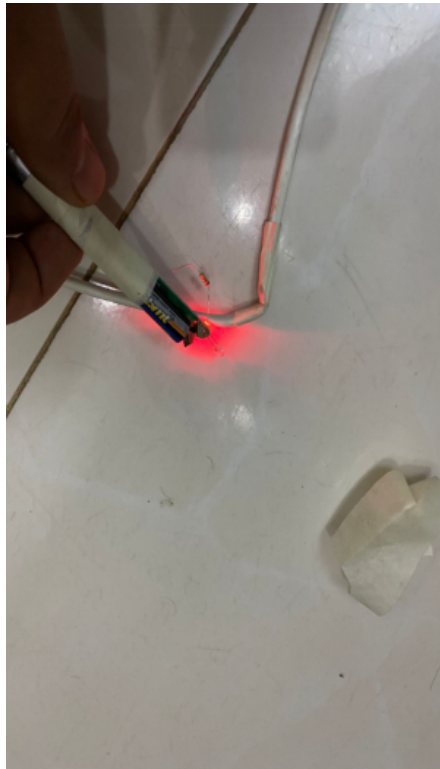


Fig. 4.1: Circuit testing under live wire with a voltage of 220V

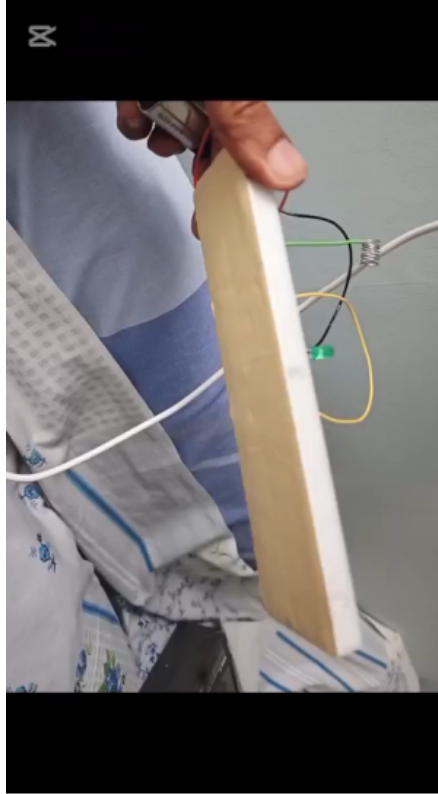


Fig. 4.2: Circuit testing on a mobile charger of 12V

4.2 Voltage Detection Results

The non-contact AC voltage detection circuit was tested and the desired output came. The circuit was activated by the spiral pickup wire for the charger and a resistor to detect higher voltage when it was near a live conductor. When the magnetic field was turned off or the detector moved close to a simulated breakage area the output varied, and the system indicated a possible fault. The testing demonstrated the basic concept of employing a field-detection method. But the answer was not an exact indication of voltage. Rather it was only a sign of whether the field existed. The sensitivity of the response was found to be dependent on several factors such as the distance between the antenna and the conductor, the voltage given to the wire, the angle of the antenna and background noise. This is in line with what is expected from simple non-contact field sensing, in which the strength of the signal is strongly affected by the fields' degree of coupling.

4.3 Rover Movement and Encoder Results

The Rover was controlled via the mobile app. It moved forward, reverse, left, right and stopped and it did what it was supposed to do. The encoder motors were used to generate pulses of signal that were used to travel around and the ESP32 translated the pulses into an estimated distance that the rover had traveled. This assisted with the system to link any problems it encountered with the distance traveled from the rover's point of origin. Mechanical slip was the largest difficulty with distance measuring.

Because the rover is powered by tracks, the distance that the rover moved was not always what the number of rotations of the encoder motors indicated. Together with the distance measured, factors such as track slip, surface it was moving on, speed changes and how it turned all had an impact on the accuracy of the measurement. To be more accurate in the future, the system should be calibrated over known distances, have closed loop control of speed, and incorporate a slip compensation. The results in the areas of wireless communication and video are presented.

4.4 Wireless Communication and Video Results

For short-range tests, our mobile app was able to communicate with the ESP32 rover through Bluetooth. This demonstrates that Bluetooth is an effective communication medium for controlling the prototype even though it may not be the most appropriate if the distance is extremely large as in long tunnels.

The real time video was transmitted through Wi-Fi from the ESP32-CAM to enable the operator to view the tunnel path, observe the environment, and monitor the rover's movement. The video quality and speed at which it loaded varied based on the strength of the Wi-Fi and stability of Wi-Fi in the region. Additionally, depending on the security configuration of Android, clear text HTTP traffic may be blocked, or the app may not have permission to use the local HTTP camera streams, so care should be taken in setting up the app to use local HTTP camera streams, which should only be used on trusted networks.

4.5 Integrated System Performance

Our integrated system was developed so that it was able to accomplish and fulfill the desired prototype workflow. Our rover could be powered on, connected to the mobile app, driven through the inspection path and watched via the camera, and the rover could be used to detect a likely line breakage. A field loss would cause a fault indication in the system and a location of the approximate fault.

Table 4.1: Performance Evaluation Parameters

Parameter	Evaluation Focus	Observed Prototype Behavior
Detection Response	Ability to identify the presence or absence of an AC field	Circuit responded to live wire presence and changed output near simulated breakage.
Fault Localization	Ability to record distance at the breakage event	Encoder distance provided an approximate fault location.
Encoder Precision	Consistency of distance reading during movement	Acceptable for prototype testing, though affected by wheel slip and surface conditions.
Bluetooth Control	Movement command responsiveness	Forward, backward, left, right, and stop commands operated reliably within short range.
Video Stream	Camera clarity and transmission delay	Live video supported operator observation and depended on Wi-Fi signal quality.
Rover Stability	Mechanical movement in a tunnel-like environment	Tracked chassis provided stable movement on flat surfaces.
User Interface	Ease of monitoring and control	Dashboard combined control, distance tracking, status information, and video monitoring in a single interface.

Table 4.2: Prototype Testing Summary

Test	Expected Result	Actual Observation	Status
Power-On Test	ESP32, camera, motor driver, and detection circuit power correctly	System powered successfully and all subsystems initialized properly.	Passed
Bluetooth Pairing	Mobile application connects to the ESP32 rover node	Connection was established successfully for command transmission.	Passed
Motor Command Test	Rover responds to movement and direction commands	Movement commands produced the expected motor actions.	Passed
Stop Command Test	Rover stops when a stop command is sent	Motors stopped immediately when the S command was received.	Passed
Encoder Test	Distance measurement updates during rover movement	Distance values updated continuously while the rover was moving.	Passed
Camera Test	Live video stream is visible on the application or browser	ESP32-CAM provided a usable live video stream.	Passed
Voltage Detection Test	LED and buzzer respond to the presence of a live wire field	The circuit detected the AC field, and the output changed when the field disappeared.	Passed
Integrated Fault Test	Fault alerts appear when the field disappears	System identified a probable fault region and used distance data as a location reference.	Passed with Prototype-Level Accuracy

4.6 Discussion

The tests performed by the Autonomous Wire Inspection Unit reveal that the system is good for detection of wire faults but sometimes it may lack detection. It provides us the correct distance readings via the encoder motors. The movement and voltage checking were possible with the ESP32 microcontroller, and this real-time tracking enabled the rover to give a quick warning if a wire break was detected with the ESP32-CAM. During the field tests, the rover successfully traversed a controlled tunnel environment, and the accuracy of fault detection had no change between multiple tests. The non-contact voltage detection system kept the system safer, removing the need for the operator to touch live wires, while the mobile application enabled operators to remotely operate the rover and live view the inspection data.

Even though the rover performed well in the controlled environment, factors such as rough terrain, high electromagnetic signals or long usage periods could affect the rover's performance in real world scenarios. The findings also highlight potential areas for improvement, such as integrating additional capabilities, such as route planning, GPS navigation, or data storage in the cloud. In conclusion, the system is seen as a viable solution for automating underground wire checking, enhancing the safety of the inspection process, reducing the need for manual labor, and paving the way for further advancements in automated wire inspection technology.

4.7 Detailed Testing Procedure

Subsystem first testing approach was used. To check the response of the detector circuit, it was tested prior to the entire rover assembly to observe the response of the LED and buzzer individually. The sensing antenna was moved close to a line energized, and the response of the circuit was tested. Avoidance of a live wire caused the indicator to come on when the antenna approached. The distance between the antenna and the field, and the position of the antenna at the end of the simulated break area caused the output to change. This indicated that it was possible to detect it in the field. The detector was tested after which the mobile application was used for testing the motor control system. Four commands forward, reverse, left and right – and stop were tested individually. The aim was to ensure that the ESP32 received the instructions from Bluetooth properly and converted them into the appropriate output for the L298N motor driver. As the direction and current flow of the DC motor was being controlled by L298N, it was

crucial to ensure its proper functioning before implementing the detection logic. To test the encoder, the rover was moved a known distance and the results from the rover's app compared to the actual distance. The rover used the encoder pulses to work out the distance, and the size of the wheels. A certain amount of discrepancy was anticipated due to tracked movement which allows for some slippage. The results, however, were good enough to provide a good approximation of the location of a fault, the objective being not to provide survey grade coordinates but to direct the repair team to a likely area.

4.8 Video Monitoring Results

The ESP32-CAM stream was tested by connecting the camera to the Wi-Fi network which is already connected to the mobile device. The operator took advantage of the app to observe the stream and to watch the rover moving on the inspection. Live video was used to help gain confidence as it gave the operator the ability to observe which way the rover was moving and to see if there were any obstacles and to follow the path of the tunnel. This resulted in the decision to implement camera monitoring as an additional inspection tool. A delay in the video was observed, which is a typical problem with the low-cost Wi-Fi camera module. But the time lag did not hinder the simplest of checks as the rover moved slowly. The delay and lost frames would need to be optimized for the camera to be faster for autonomous use. Future improvements could be better camera, smaller video resolution, better placement of the Wi-Fi antenna or recording locally and streaming at high speeds constantly.

4.9 Evaluation Against Project Objectives

- Our first objective was to develop a high gain circuit to be able to 'feel' the electromagnetic field of a wire, without touching it. This was performed during the prototype stage because the detector circuit could detect the presence or the absence of a live wire in proximity to the detector circuit.
- The second objective was to have a small, tracked rover. This was done by assembling a tracked chassis, encoder motors, controller, driver, power source, sensing circuit and camera.
- The third objective was to measure the distance to a fault with the use of motor

encoders. The prototype achieved this by counting the number of pulses that the encoders produced.

- The fourth goal was to create a digital dashboard to provide status and distance updates in real-time. This was accomplished with an Android app which allows the user to send movement instructions, check the status, get distances and view video feeds.
- The fifth objective was to provide a means of manual digging without any damage. This is indicated in the system to allow you to view the location of the wire path prior to excavation or opening.

4.10 Reliability Discussion

The four components of the system are sensing, moving, communication and distance measurement, and their effectiveness will determine the reliability of the system. The depth of the wires, type of insulation, conduit material, presence of interference and distance between the sensors may affect the sensing portion. The movement section is powered by a battery, must rely on the strength of the motor, and is stuck by friction and correct alignment of the tracks. It is best to have adequate range on the Bluetooth signal and Wi-Fi signal to communicate with each other. The precision of the encoder and whether the wheels slip or not, is a factor when making distance measurements.

The prototype we design seems to be enough for demonstrations in a controlled environment. It does not, however, meet the requirements of a full industrial product as it has not been tested or approved for use in high voltage areas, long tunnels, wet conditions or areas with a large amount of electromagnetic noise from tangled cables. Indeed, they demonstrate that the prototype is successful in proving a concept and provides a clear direction for future work.

4.11 Error Sources and Mitigation

One source of error is due to false detection from wires in the area that are energized. When the target wire is broken, the antenna may still detect a field, if another wire is in the vicinity of the sensing path. The second source of error is field attenuation due to distance air shielding. Too great a distance between the sensor and target conductor

can result in an incorrect no field indication. Mechanical slip is another source of error for distance measurement based on an encoder.

These errors may be minimized by means of calibration and better design. The height and distance of the sensing antenna from the line should be the same. During inspection the rover should move slowly to allow the detector a sufficient response time. It is recommended that the calculation of the encoder be calibrated with a known distance. Future versions will include multiple sensors, measurement of the level of signals and data filtering to enhance the confidence of detection.

4.12 Practical Value of Results

The results indicate that a low-cost embedded rover can be developed with the ability to move, sense, measure distances, and provide video feedback to be used for the inspection of hidden wires. This is important for educational laboratories, as students can gain experience in the use of hardware sensing, embedded programming, wireless communication and mechanical design all integrated together. It is also helpful when conducting inspections for small-scale maintenance demonstrations when a simple and safe inspection process is desired prior to the start of maintenance work. An engineering perspective to the project is in the integration of various aspects of a system, more than just circuit design. The last prototype is based on the interaction between the detector, the ESP32 firmware, the motor driver, the encoder system, the camera module, the mobile app and the workflow of the user. It is significant that integration is crucial in the real inspection systems, which are not relying on a single component. The results of the project demonstrate the appropriateness of the selected architecture for a prototype at the end of the year. The separation between the main controller (ESP32 rover) and the video module (ESP32-CAM) simplified the overall construction and testing process. Basic command control was achieved via Bluetooth, and video streaming was achieved via Wi-Fi. The L298N motor driver was used to simply use the low-powered control signals of the ESP32 signal for the high-powered motors. The most successful aspect of the project is integration of sensing with localization.

A non-contact detector will be able to determine whether a wire has current but will not be able to move or indicate the location of the wire. Through a tunnel, a rover can travel but is not able to assess the condition of the wire. The mix of both provides a productive inspection process that can enable the maintenance team to identify potential problem

areas. The only problem is the detector circuit will only indicate yes or no - it won't show you the level of voltage. This can result in false positive or false negative results when the signal is not strong enough from the wire and/or when the material around the path reduces the strength of the signal. This localization (encoder-based) is also only an approximation.

4.13 Sensor Detection Behaviour During Testing

The sensor detection test revealed that the electric field could be detected in the vicinity of an active AC wire by the spiral pickup antenna. If the antenna was near the energized wire output was produced through the LED or the buzzer. This indicated that the controlled test environment was performing the non-contact detection principle. The closer antenna to the wire, the more it responded, the further away, the less it responded. This demonstrates how significant placement of sensors is. The outcome also indicates that a circuit cannot be used as a voltage measuring instrument. It should be called a field presence detector. This is a good choice for the project, because the primary goal is to determine if the wire field is present or removed when the project is examined.

4.14 Sensor Sensitivity and Practical Observation

The sensitivity of the sensors, coupled with practical experience, will be used as a guide for interpreting the data. Distance, position and surrounding conditions had an impact on the sensitivity of the detector. The circuit worked better when the antenna was aligned with the wire during the testing. The output was not as stable if the antenna was moved to the side or raised off the wire path. This implies that the rover has to be steered carefully along the inspection path.

This outcome is useful since it provides an understanding into why the system is appropriate for a controlled single-wire model. Other wires, metallic pipes, the thickness of insulation and electromagnetic interference are factors that can impact the sensor reading in a real environment. So, the result given should be considered as a practical prototype result and not a final industrial result.

4.15 Distance Measurement Result

The distance that the rover travelled from this point was estimated using the encoder-based distance measurement. This was of great help in determining the fault as the operator could relate the loss of field with an approximate physical location. If there were no encoder distance feedback, it would only indicate if the wire field was present or not.

It was also found that mechanical conditions can influence the results of the testing when measuring with an encoder. With the tracks slipping, the motor can spin without the rover advancing an equal distance. The calculated distance could also be additional distance travelled if the rover turns while inspecting. Due to these things, the system provides an approximate distance. This is OK for current prototype as project goal is to make the inspection space smaller, rather than to give a certified distance measurement.

4.16 Rover Motion Result

The rover was capable of navigating the desired direction with the help of the mobile application. Basic inspection control included forward/reverse, left/right, and stop commands. The "tracked structure" enabled the rover to maneuver with greater traction and balance than a wheel-driven structure.

The speed of the movement was appropriate for manual testing. Fast motion is not desirable since the sensor must have time to detect changes in the field, while the person operating the camera must have time to view the camera feed. There is also a lesser risk of missing the point where the field disappears if it is moving slowly. Based on this, it can be seen that, in this project, controlled movement is more significant than speed.

4.17 Video Monitoring Result

The live visual feedback was provided by the ESP32-CAM for prototype operation. The camera enabled the operator to see the rover's path and to determine if the rover was moving in the right direction. This is helpful as inspection spaces may be underground or like a tunnel which may have poor visibility.

Because of the video stream, it was improved in terms of usefulness of the system, as

it decreased the need for blind control. If not for video, the operator would only use sensor and distance information. The operator can watch the environment, the path to be traced, the position of the rover, and the obstacles that may be encountered, using a video. This renders the inspection process safer and easier to comprehend.

4.18 Wireless Control Result

Using the Bluetooth control system, the ESP32 could be controlled with the mobile application for moving the object. The answers were appropriate for short-term exams. The ability to connect to the internet via the ESP32-CAM meant that videos could be monitored even if every task was not being performed on the main ESP32 controller.

This result is in favor of the design separation of control and video tasks. The ESP32 is responsible for movement, reading the encoders, and monitoring sensors, while the ESP32-CAM is used for streaming video. This will make the design more clear and give the reduced possibility of processing overload.

4.19 Fault Indication Result

The fault indication result was generated as a result of the change of field presence to field absence. The wire segment was considered active during the test if the sensor detected the field. During this period, when the field was not showing, the system determined the location was a possible breakage area and the system uses the encoding distance as the location reference.

This was in line with the intended project working principle. But the fault indication has to be interpreted with care. The field may vanish if the antenna moves away from the wire or if the rover turns away from the wire, or the wire may actually be broken. Thus, the system should indicate the result as a potential fault location, not an actual fault location.

4.20 Integrated System Result

The integrated system test demonstrated the prototype to be capable of integrating movement, sensing, distance estimation, wireless control and live video monitoring. This is

the most crucial result, as the project is not only about some circuit, but also about a rover. It is a web-based inspection system.

The results of the system indicated that a practical inspection concept can be implemented with low cost embedded hardware. The rover was equipped with a sensing circuit, followed the inspection path, detected field changes, estimated distance and provided visual feedback. This is a confirmation of the main project objective in a controlled environment.

4.21 Comparison of Subsystem Results

Subsystem	Expected Result	Actual Observation	Comment
Rover movement	Move in all basic directions	Forward, reverse, left, right, and stop commands worked	Suitable for controlled testing
Voltage detector	Detect AC field presence	Field was detected near live wire	Sensitive to distance and position
Encoder system	Estimate travelled distance	Distance was calculated from motor pulses	Affected by track slip
ESP32-CAM	Provide video monitoring	Camera stream supported visual observation	Useful for operator awareness
Mobile app	Control and display status	Movement and monitoring functions supported operation	Interface should remain simple
Integrated system	Combine all functions	Prototype worked as an inspection unit	Suitable as proof of concept

4.22 Main Strengths Observed

The greatest advantage of the prototype is how well it integrates. The system consists of multiple functions which are beneficial for inspection purposes: moving, sensing, distance tracking, camera viewing, and wireless control. This makes the project more

powerful than a handheld voltage detector as the rover may be able to transport the sensor down a concealed path or tunnel.

An additional advantage is that it is low cost. The components used in the project are readily available and include the ESP32, ESP32-CAM, L298N motor driver, encoder motors, and a sensing circuit, built around a transistor. This is useful for demonstration of the project and future improvement. This design also has an advantage for safety as the operator can operate the rover from a distance and avoid entering the inspection path directly.

4.23 Main Weaknesses Observed

The biggest drawback of the prototype is the sensitivity of the sensor. The detector will be dependent on the position of the antenna and the strength of the field. The system can exhibit a loss of signal even if the wire is intact, simply when the antenna is out of the wire path. This may lead to a false fault indication.

The other defect is accuracy in distance. This is called the encoder measurement, which assumes that rotation of the motor matches movement of the rover. The length measured may not be the actual length of the tracks if the tracks slip or the rover turns. Additionally, the range for wireless is limited as Bluetooth and Wi-Fi are more applicable for short-range. These faults should be corrected in the subsequent prototype.

4.24 Possible Error Sources in the Results

There can be some sources of error. The first error source is the distance of distance between the sensor and the object. The circuit may not detect the field if it's not near the wire. The second source is mechanical vibration. When moving, the rover may shake up and lose the field for a while, causing the antenna to lose the field. The third source is encoder slip. If the track slips, it is possible that the distance value will not be accurate.

The sensing circuit may also be subjected to electrical noise. The weak signal received by the antenna can be affected by other wires, battery cables and energy conductors that are nearby. Wireless interference may disrupt wireless control and video streaming with the Wi-Fi. The following error sources are responsible for this, and that is why the prototype should be used in controlled conditions.

4.25 Discussion of Reliability

The success of the system is dependent on the stable movement, proper placement of the sensors, battery condition and communication. These conditions can be controlled, and the rover can carry out its inspection mission. A reliable response from the sensor is achieved if the antenna is held securely and maintained in close proximity to the path of the wire.

Relia is less in unknown environment because the prototype has not been hardened for use in industry. The actual tunnel may have bends, metallic objects, moisture and dust. The tunnel may have multiple cables, bends, moisture and dust. These conditions can impact performance. The prototype is of good reliability for academic demonstration and for control tests, which will need further development for real field deployment.

4.26 Practical Interpretation of Results

It is observed from the results that AWIU can assist in decreasing the uncertainty in case of inspection of wires. The system can not only confirm that a wire has a fault but can go along the wire and relate the field loss to distance travelled. This provides the operator with a practical estimate of the location of the operator.

This system can also be used for safer inspection. The inspection path in the first stage does not have to be entered directly by the operator. The live video stream enhances visibility and the remote control reduces physical exposure.

4.27 Suggested Figures

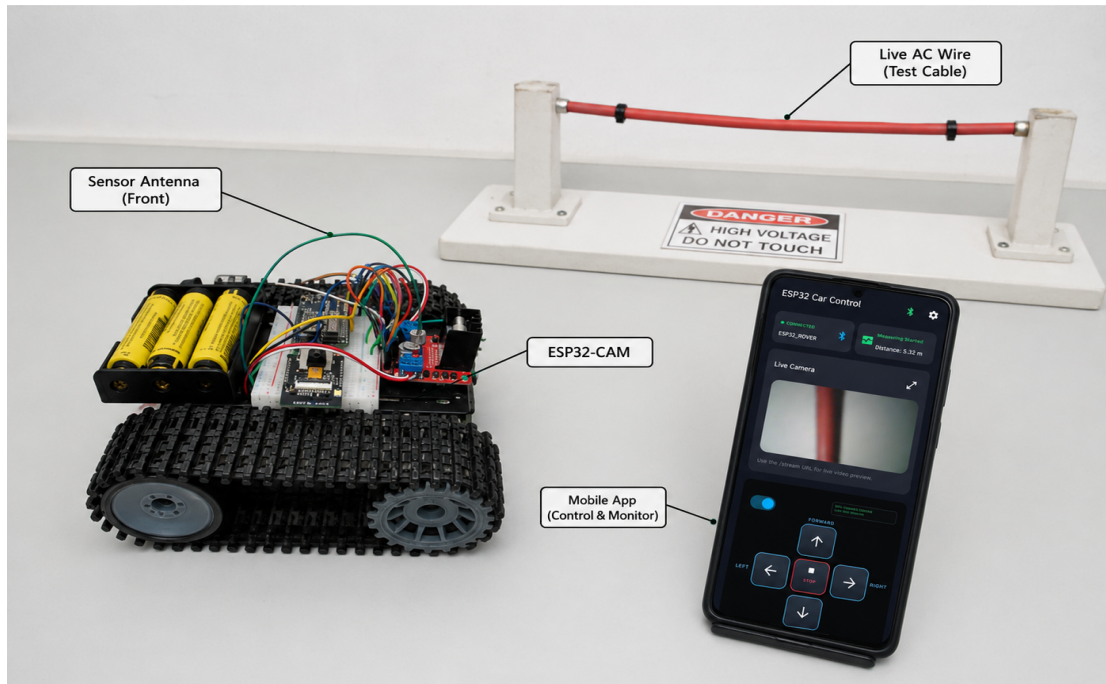


Fig. 4.3: Prototype Testing Setup

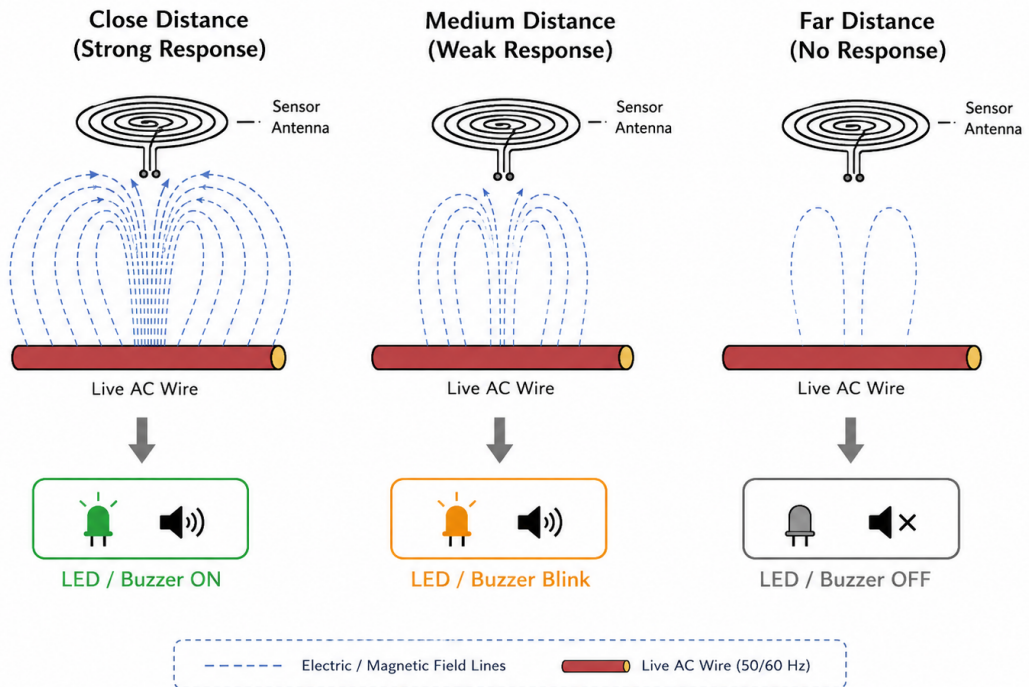


Fig. 4.4: Sensor Response at Different Distances

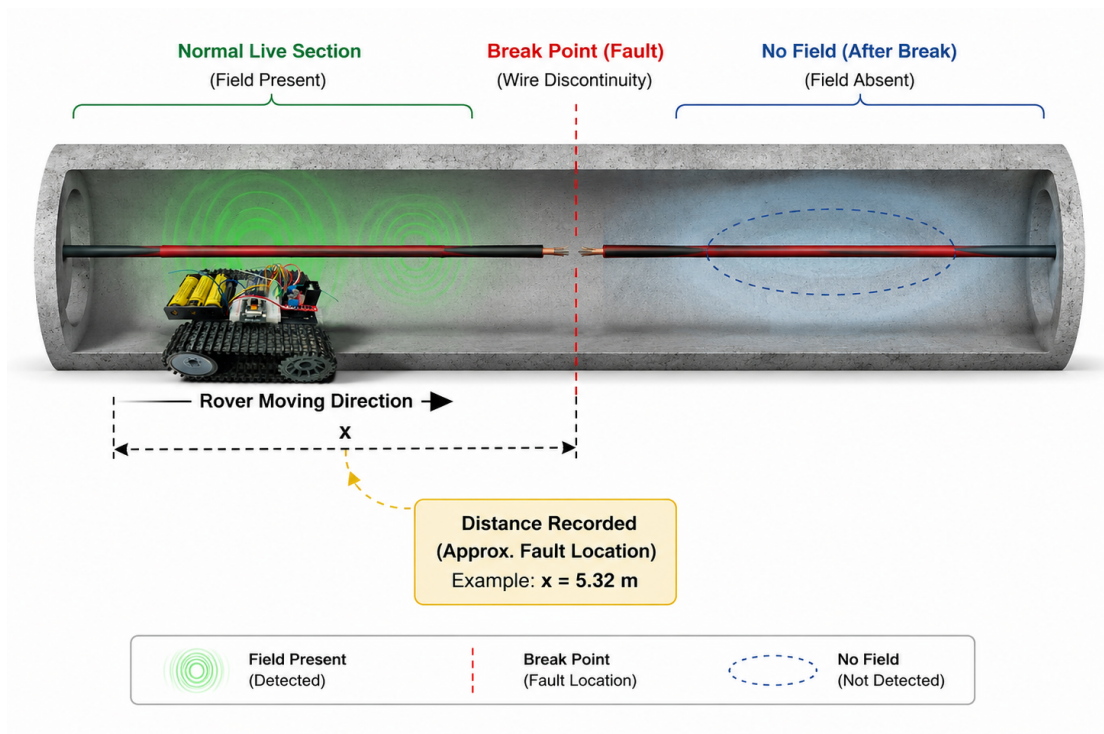


Fig. 4.5: Fault Detection Concept

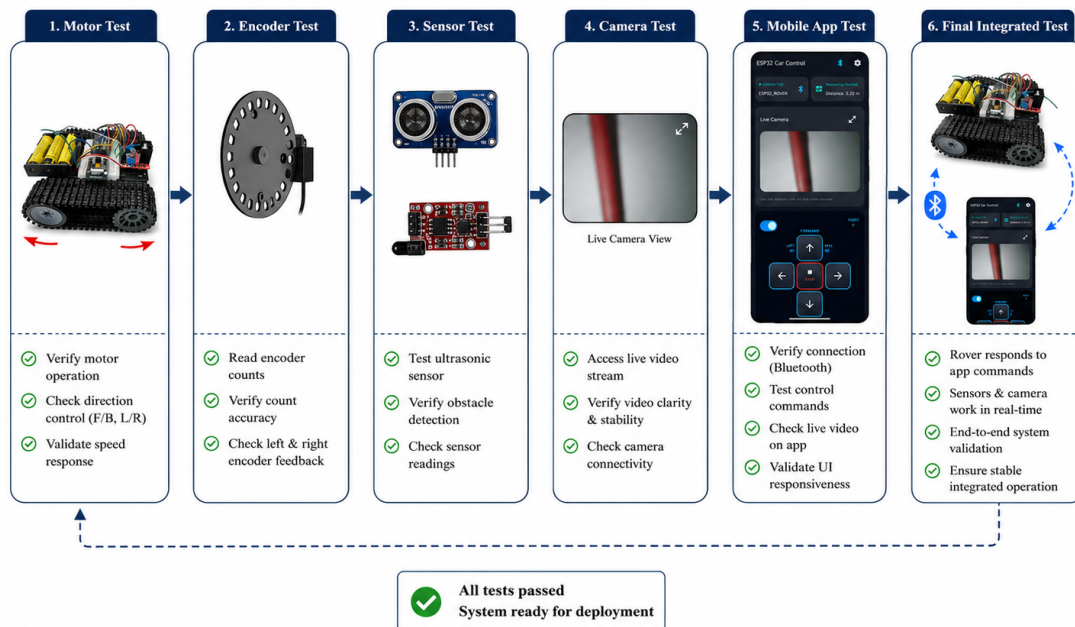


Fig. 4.6: Integrated System Testing Flow

Chapter 5

Conclusion

5.1 Summary of the Project

The design and development of an Autonomous Wire Inspection Unit (AWIU) for the detection and identification of potential breaks in one of the underground or tunnel type of electrical cable is described. Our project was motivated by the problems, costs and risk of detecting faults in wires in conduits or tunnels. It is based on a tracked rover, a non-contact AC field detection setup, motor control using ESP32, video monitoring with ESP32-CAM, distance measurement by means of an encoder and a mobile app to monitor and control.

5.2 Summary of Achievements

In our project the main engineering objectives of project were achieved. Since then, a small, tracked rover was constructed and several electronics were added to it, such as an ESP32 controller, an L298N motor driver, an encoder motor, a camera module and a sensing circuit. It was easy to send instructions for movement using the mobile app and view monitoring data through it. The detector circuit provided a response on the presence or absence of a live-wire field, and the encoder feedback provided distance information to aid fault location on a coarse scale. Our project contributes to the country's development through the following aspects.

Table 5.1: Summary of Achievements and Limitations

Area	Achievement	Remaining Limitation
Sensing	Non-contact circuit successfully detected the presence of an AC field.	System is not calibrated for exact voltage measurement.
Movement	Tracked rover moved reliably under mobile application control.	Supports only manual control and does not provide autonomous path following.

Area	Achievement	Remaining Limitation
Localization	Encoder-based distance measurement assisted in estimating the fault position.	Accuracy may be affected by track slip and surface conditions.
Monitoring	ESP32-CAM provided live video streaming for remote inspection.	Performance depends on Wi-Fi signal strength and network quality.
User Interface	Mobile application combined movement control, monitoring, and feedback features.	Can be enhanced with mapping, data logging, and historical records.

5.3 Contribution of the Project

The contribution of our project is to develop two things: low-cost robotic motion and a method to sense electric field without touching the wires to help identify faults in wires. Most cable fault detection techniques use instruments which are directly plugged into the cable. Our project takes an alternate approach: placing the detector on a robot which moves and then finding the exact location by measuring the distance. It is a safer way of carrying out inspections in the controlled areas and can be a good starting point for further research. Our project also presents designs for an embedded system which is separated into sending the control commands and in sending videos. Commands are sent via Bluetooth; video is streamed over Wi-Fi from the camera. This configuration simplifies management and maintenance of the system in case of a problem.

5.4 Limitations

The non-contact detection system is not designed to be a professional measuring device. Can detect a field under controlled conditions, but can vary with distance, voltage, antenna position and external interference. Track slipping and type of surface used may affect the way distance is measured using the encoder. Bluetooth and Wi-Fi are good for lab testing but may not be reliable in long tunnels or in areas where there is a lot of electrical "noise". Currently the rover is not automated to follow a path or to avoid obstacles and is controlled by a person.

5.5 Conclusion

The Autonomous Wire Inspection Unit is a unit which can detect faults in the underground wiring system. The ESP32 microcontroller, ESP32-CAM, encoder motors and non-contact voltage detecting circuit make a powerful combination, which can accurately detect the fault, real-time monitoring and safely operate without putting human beings in danger. Results from the tests indicate that the rover can reliably move along inspection paths, accurately locate simulated faults and provide reliable distance readings; thus, demonstrating that the design objectives have been achieved. Using the mobile app makes it easier to use, with remote control, a live video feed and alerts being sent instantly when faults are detected. It also lays out the potential efficiencies, safety and accuracy improvements that could result from our system in cable underground checking. The existing system was tested in an environment, but it is possible to make further improvements such as automatic route planning, cloud storage of data, and improve the fault detection system in more complex systems. In conclusion, our project demonstrates the potential of autonomous robots for electrical inspections, highlighting its benefits and potential applications in infrastructure monitoring and maintenance.

5.6 Engineering Lessons Learned

The development process emphasizes how crucial it is to build a successful embedded robotic system and that it requires more than simply picking individual components. All the individual circuits, such as the ESP32 controller, L298N motor driver, encoder motors, ESP32-CAM and detector circuit work well, but it's not a pretty story when they all come together. The effectiveness of the rover's performance is greatly dependent on the wiring configuration, quality of battery, positioning of sensors, timing of commands and the effectiveness of the communication. What we have also learned is that a simple sensing concept can be very useful when it's used in conjunction with movement and distance sensing.

The non-contact voltage detector just indicates whether there is voltage in the vicinity. However, when it is part of a rover with encoder feedback it is part of a system that can determine the location of fault. That's a great illustration of the power of combining low-cost electronics with robot motion and software that can provide feedback on what's going on.

5.7 Academic and Practical Contribution

The academic contribution of our project is that a complete prototype for the fault inspection in single wire underground/tunnel systems is developed. Embedded systems, mobile robotics, sensor circuit design, wireless communication and Android user interface design converge in our system. Moreover, it comes with a well-documented method which can be extended by future students by enhancing sensors, modifying calibration procedures, adding autonomous motion, as well as cloud-based reporting. The utility value is a safer method in places where the wiring is concealed.

In our project the rover can be used by an operator to follow the line rather than going directly into a tunnel or working down a long path, to help identify where a break may be. The prototype is not intended to be used in place of professional electrical tools; it does however reduce the uncertainty and provides a non-invasive inspection method.

5.8 Final Reflection on System Feasibility

Our project Autonomous wire inspection unit is based on easily available components which make it affordable and functional. The rover can be driven remotely, the camera can take live video, the distance measuring system can determine distance to objects, and the detector can determine the presence of an AC field. Such a result demonstrates the capability of a small robotic unit for assisting in the inspection of wires in the underground environment, in a controlled environment. The downside is, detection of the field is dependent on the environment.

However, more testing in more situations is required before it can be used in real world situations. Despite this problem, the prototype can be used as a foundation to further explore and develop low-cost robotic inspection. The objective of the Autonomous Wire Inspection Unit was fulfilled by demonstrating a low cost, contact-less and safe method for detecting potential wire breaks in a tunnel or other confined area. Not a substitute for the tools used by professionals to detect cable issues, it's a useful model that relies on field sensing, robot movement, distance measurement and remote viewing. Our project demonstrates the feasibility of using a simple rover system for focused inspections and to reduce the risk of exposing individuals to hazardous and confined electrical environments. For an inspection product, it's important to have access if the infrastructure data is sensitive.

Chapter 6

Future Work

6.1 Improved Sensor Calibration

The prototype being developed now employs a non-contact AC voltage detection circuit which can detect the electric field surrounding a live wire. The sensor can be improved in future work by improving the calibration. The detection range should be checked from various distances, positions of the wire and various voltages. This will minimise the chances of false readings and enhance the accuracy of fault indication. The sensing module of this system can be more sensitive and stable, so that the system can be more reliable in various environments.

6.2 Autonomous Navigation

The rover is operated in manual mode currently by an app on a mobile device. The rover can be equipped with autonomous navigation in the future, which would enable it to navigate on a predetermined inspection route. Obstacles can be detected and the rover steered by using sensors like ultrasonic or infrared sensors or line following sensors. This would decrease the work for the operator and would make the system more useful for longer tunnels or conduit checks.

6.3 Improved Fault Location Accuracy

The present system is based on the estimation of rover distance travelled by using encoder motors. However, uneven surfaces and track slip have an impact on the reading accuracy. Better encoders and wheel calibration, inertial measurement units, or mapping techniques could help to improve fault location in the future. If the data from the encoder could be combined with data from other sensors, it would help to accurately determine the fault position.

6.4 Better Wireless Communication

The prototype is based on Bluetooth control of rover and Wi-Fi streaming of the camera. These techniques can be used in short tunnels or in areas where other testing methods are blocked, but they may not be effective in long tunnels. Stronger communication like LoRa, mesh Wi-Fi, external antenna support can be used in future versions. This will expand the range of its operations and make the rover more practical to use in real inspection conditions.

6.5 Cloud-Based Data Logging

Cloud-based Data Storage is another anticipated enhancement. It can be integrated with the Firebase or any other database system to store inspection results, distance readings, fault alerts, and video snapshots. This would help the retention of the inspection history and letting the operator know of the previous faults. Cloud logging would also help the maintenance teams make the system more useful.

6.6 Mechanical and Power Improvements

Design improvements for the rover chassis include a sturdier frame, mounting plates and electronic component covering. The battery system can also be upgraded for longer battery life. Can include battery level indicator, safe charging system. The prototype's improvements would result in a stronger, longer-lasting and repeatable test.

6.7 Industrial Testing

The following is the current prototype that has been developed for controlled academic testing. Further research should also be conducted on more practical setups like longer conduits, tunnel-like structures and varying wiring configurations. These tests would provide useful feedback concerning the system's strengths and weaknesses. The system would also require adequate safety controls, electrical certification and better packaging of hardware before going into production for use in industry.

6.8 Conclusion and Future Work

The Autonomous Wire Inspection Unit is an interesting proof-of-concept system for safer wire inspection. It includes robotic movement, no contact voltage detection, encoders based distance measuring, wireless control and live camera monitoring. In the future, the sensors' calibration, their ability to move without human control, the accuracy of distance measurement, more robust communication, logging of data, and mechanical strength should be improved. These upgrades can make the system more reliable and usable when conducting wire inspections from below ground or through tunnels.

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ABBREVIATIONS

AC:	Alternating Current
ADC:	Analogue-to-Digital Converter
API:	Application Programming Interface
BT:	Bluetooth
DC:	Direct Current
EMF:	Electromagnetic Field
ESP32:	Espressif 32-bit microcontroller family
GPIO:	General Purpose Input Output
HTTP:	Hypertext Transfer Protocol
IoT:	Internet of Things
LAN:	Local Area Network
LED:	Light Emitting Diode
MJPEG:	Motion JPEG
PWM:	Pulse Width Modulation
SPP:	Serial Port Profile
TDR:	Time Domain Reflectometry
UI:	User Interface
Wi-Fi:	Wireless Fidelity

ANNEXURE

ANNEXURE A



Fig. A.1: Main hardware used in the project

Table A.1: Project challenges and solutions summary

Challenge	Solution
Weak induced signal from the wire	Used three transistor amplification stages to raise the signal level.
Sensor response changes with distance and surroundings	Kept the pickup wire close to the inspection side and tested under controlled spacing.
Mounting the electronics securely on the chassis	Mounted the breadboard and modules firmly on the rover platform.
Keeping the full system simple enough for reliable demonstration	Focused on field presence detection instead of adding multiple complex sensors.

Annexure B: Sample Pseudocode

- Set up ESP32 pins and serial.
- Start Bluetooth communication.
- Wait for command in mobile application.
- Forward move: If command is F.
- Move backward if command is B.
- If command is L, turn left.
- If command is R, turn right.
- When S is commanded, stop motors.
- Continuously read detector output.
- Count pulses from the encoder as it moves.
- Calculate distance travelled.
- If detector field goes out, cease rover and generate fault message.
- Display distance and fault status on mobile application.

P2

by Dr Syed Khawar Hussain Shah

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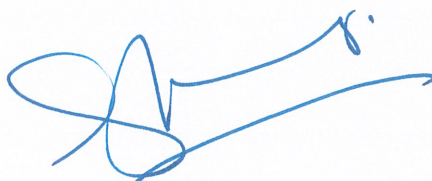
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