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RF Based Surveillance Robot with Infrared Night Vision

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ABSTRACT :

This paper presents the design and implementation of a compact mobile surveillance robot integrating infrared-capable visual monitoring, ultrasonic obstacle avoidance and inductive metal detection. The prototype uses an ESP32 DevKitC as the main controller and a separate ESP32-S3 camera module to provide a live MJPEG stream over a local Wi-Fi network. An HC-SR04 ultrasonic sensor mounted on an SG90 micro-servo scans the forward environment, while an L298N dual H-bridge driver controls two TT geared DC motors in a differential-drive arrangement. An A88 inductive metal detector provides a digital detection indication and audible alert, and a 16×2 I2C LCD displays local operating information. Power is supplied by two 3.7 V 18650 lithium-ion cells connected in series and regulated to 5 V using an LM2596 buck converter. The modular architecture separates motion control from video streaming, allowing the robot to continue sensing and reacting while visual monitoring operates independently. Tests documented in the project report indicate functional ultrasonic ranging, local video streaming, metal response to test samples and stable operation during the reported trials. The prototype is intended for educational demonstration and preliminary inspection, rather than certified security or hazardous-material detection.

Keywords: Surveillance robot, ESP32, infrared night vision, ultrasonic sensor, obstacle avoidance, metal detection, Wi-Fi video streaming.

1. Introduction

Mobile surveillance platforms can support observation of dark, restricted or difficult-to-access locations while reducing the need for a person to enter the area. A useful low-cost platform should combine movement, visual feedback and basic environmental sensing without requiring a high-performance single-board computer. Existing surveillance robots commonly focus on remote video, obstacle avoidance or metal sensing individually. Integrating these functions into a small mobile platform provides a more versatile educational prototype [1]–[5].

The project described here evolved from an initial RF-controlled night-vision concept into an ESP32-based architecture. In the implemented system, the main ESP32 DevKitC manages locomotion, ultrasonic sensing, metal-detector polling and LCD updates. A separate ESP32-S3 camera subsystem captures images and streams them over a local Wi-Fi network. The separation of control and video processing is intended to keep movement decisions independent of camera-stream activity.

The design also addresses the practical need for a compact system in which sensing, computation, communication, actuation and power management operate together. Rather than relying on a high-performance single-board computer, the architecture separates the main control tasks from the camera-streaming task. This modular arrangement supports incremental testing and makes individual functions easier to troubleshoot.

The scope of the present work is limited to a mobile prototype operating on relatively flat surfaces. It demonstrates local obstacle response, preliminary metal-object indication and visual monitoring; it does not implement GPS navigation, persistent environmental mapping, cloud logging or advanced on-device object recognition.

1.1. Objectives

The objectives are to: (i) develop a compact two-wheel-drive robot; (ii) provide low-light visual monitoring through an infrared-capable camera; (iii) detect nearby obstacles using servo-scanned ultrasonic ranging; (iv) provide an audible and LCD indication when the inductive detector senses metal; and (v) implement a regulated battery supply using commonly available modules.

1.2. Scope of the Work

The work concentrates on integrating the mobile platform, local sensing and wireless visual monitoring into one demonstrable prototype. The main controller handles movement-related decisions and display updates, while the camera module provides a separate visual channel. This arrangement allows the individual functions to be tested separately before the complete system is operated together.

1.3. Design Considerations

The principal design considerations are simplicity, modularity, availability of components and suitability for a student-level demonstration. Sensor readings must be available to the controller, motor commands must be passed through a driver stage, and the camera must be able to stream without becoming part of the main movement-control loop. The system also requires a regulated supply and common electrical reference for the connected modules.

2. Related Work

Prior work on surveillance robotics has explored wireless camera control, night-vision imaging, autonomous patrol and networked decision-making. Witwicki et al. [10] discuss decision-making frameworks for networked surveillance robots, while Lee et al. [14] examine an indoor self-propelled surveillance vehicle. Other work cited in the project report considers RF-controlled spy robots with night vision [11], wireless night-vision surveillance with metal detection [12], and nighttime object detection for security patrol [13].

Obstacle-avoidance systems frequently use ultrasonic ranging because it is inexpensive and straightforward to interface with a microcontroller [4]. Camera-based systems using Wi-Fi or IoT communication enable remote observation [9], while inductive sensing can provide a simple binary indication of nearby conductive objects [5], [6]. The present prototype combines these capabilities using a modular ESP32 control architecture. The references below are reproduced from the supplied project report; bibliographic details should be verified against the original publications before external submission.

3. System Design and Methodology

The system is divided into power, control, sensing, actuation, vision and feedback blocks. The battery pack supplies the LM2596 buck converter through an on/off switch. The regulated 5 V rail powers the documented electronic modules. Common ground provides a shared reference. The main ESP32 receives the HC-SR04 echo signal, commands the SG90 servo and L298N motor driver, reads the A88 detector output and updates the LCD. The camera module is powered separately from the same regulated rail and streams video independently. The complete circuit is shown in Fig. 1.

3.5 CIRCUIT DIAGRAM

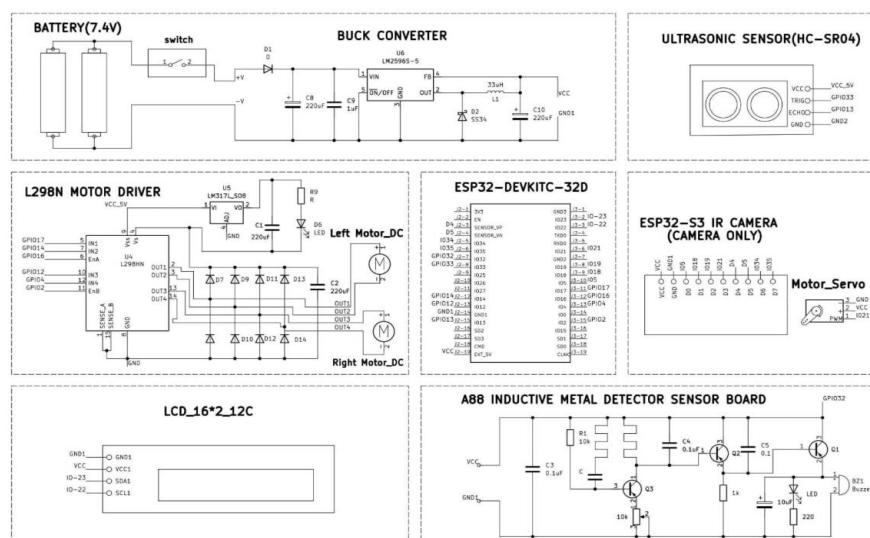


Figure 3.1: Circuit diagram of the robot

Fig. 1. Circuit diagram of the surveillance robot (from the supplied project report).

The system is organized into six functional blocks: power supply, control, sensing, vision, actuation and feedback. The control block repeatedly acquires sensor information and coordinates the robot's response. The sensing block supplies distance and metal-detection inputs, the actuation block changes the robot's motion, and the feedback block presents concise operating information to a nearby observer. The camera subsystem forms a parallel visual path over the local wireless network.

The design uses a nominal 7.4 V battery source formed by connecting two 3.7 V cells in series. An on/off switch provides a means of isolating the supply, and the LM2596 buck converter provides the regulated 5 V rail described for the prototype. Common grounding establishes a shared electrical reference. Motor startup current and converter loading can influence supply stability, so wiring quality and current capability remain important design considerations.

3.1. Main Controller and Motion System

The ESP32 DevKitC coordinates sensor readings and motor commands. The L298N provides two H-bridge channels for the left and right TT geared motors. Driving both motors in the same direction moves the chassis forward; reversing both produces reverse motion, while unequal motor commands generate a turn. PWM-capable enable signals may be used to regulate motor speed. The driver carries motor current, so the ESP32 is used for logic-level control rather than directly powering the motors [8].

3.2. Obstacle Detection

The HC-SR04 measures distance from the round-trip travel time of an ultrasonic pulse. The trigger input is connected to GPIO 5 and the echo output to GPIO 18 as listed in the report. The sensor is mounted on an SG90 servo so that the controller can sample more than one direction. If the forward distance is above the selected safety threshold, forward motion can continue. If an obstacle is too close, the controller stops the motors, compares the scanned directions and turns toward the direction with greater available clearance. The sensor's stated nominal range is approximately 2–400 cm; actual performance depends on target geometry and the test environment.

3.3. Metal Detection and Display

The A88 inductive metal-detector module contains its own sensing and threshold circuitry and exposes a digital output to the ESP32. When a metallic target is detected within the module's effective range, the module's onboard buzzer gives an audible alert and the controller updates the LCD. The 16×2 I2C display uses GPIO 21 for SDA and GPIO 22 for SCL. The report describes trials with steel screws, nails, aluminium foil and copper wire. Detection distance varies with target size, material, orientation and surrounding interference; therefore, the module is used for preliminary object screening rather than safety-critical detection.

3.4. Camera and Wireless Monitoring

The ESP32-S3 camera module captures image frames and exposes an MJPEG stream through a lightweight web server over the local Wi-Fi network. The operator accesses the stream using a compatible browser or client. Infrared capability supports viewing in low-light test conditions. In the current implementation, the camera provides visual monitoring only; advanced object recognition, cloud recording and image-based autonomous navigation are outside the project scope.

3.5. Power Supply

Two nominal 3.7 V, 2600 mAh 18650 lithium-ion cells are connected in series to form a nominal 7.4 V pack. An SPST switch isolates the battery, and an LM2596 buck converter reduces the voltage to a regulated 5 V rail. The report describes this rail as supplying the controller, camera, sensors, LCD and motor supply in the prototype. Motor startup current and converter loading can affect supply stability; battery protection, suitable wiring and checking the converter's current rating are important for safe operation.

3.6. Control and Feedback Sequence

The control sequence begins with power-up and initialization. The controller configures its input and output interfaces, initializes the LCD and servo, and places the motor outputs in a safe state. It then repeatedly reads the ultrasonic sensor and the metal-detector output. Distance information is evaluated before a movement decision is made, while a metal-detection event produces an audible alert and an LCD update. The camera continues its separate streaming task in parallel.

3.7. Design Rationale

The use of separate controller and camera subsystems avoids assigning all sensing, movement and video-streaming work to a single program. The main ESP32 can focus on recurring control tasks, while the ESP32-S3 camera handles image capture and transmission. The L298N is used as the motor-current interface, allowing the controller to provide logic-level direction and enable signals instead of driving the motors directly.

The system's decision process is deliberately reactive. It uses current sensor measurements to decide whether to proceed or change direction, rather than constructing a stored map of the environment. This reduces the computational requirements and keeps the control logic suitable for the selected microcontroller. The trade-off is that the robot has only a limited view of the surroundings at any instant, so scan positions and the chosen safety threshold affect its response.

Local feedback is retained even though the robot provides wireless video. The LCD can show a short status message without requiring the operator to open a serial monitor or rely entirely on the video stream. The metal detector's audible indication provides another immediate cue. Combining these feedback methods makes the prototype easier to demonstrate and helps the observer identify the system's response during controlled tests.

4. Implementation and Operating Sequence

Implementation was performed in stages: battery polarity and converter output were checked first; the main controller and LCD were tested; the ultrasonic sensor and servo were integrated; the motor driver and motors were tested; the A88 detector was connected; and finally the camera stream was configured. Individual subsystem testing before integration helped isolate wiring and firmware problems.

At startup, the controller initializes the GPIO interfaces, LCD, servo, ultrasonic sensor and motor outputs, placing the motors in a safe state. During the repeated control loop, the servo positions the sensor, the controller obtains a distance estimate and compares it with the safety threshold. A clear path permits forward movement; a blocked path causes the robot to stop and select a turning direction. In parallel, the controller polls the metal-detector output and updates the LCD when a detection event occurs. The ESP32-S3 camera initializes the image sensor, joins the local Wi-Fi network and starts the stream server independently.

The firmware is developed in the Arduino IDE with ESP32 board support. The main-controller program initializes the GPIO interfaces, display communication, servo control, ultrasonic measurement and motor outputs before entering the repeated control loop. The camera program is maintained separately and is responsible for image acquisition and the MJPEG streaming service.

During obstacle response, the controller positions the distance sensor at a scan angle, triggers a measurement and estimates distance from the echo duration. It compares the result with a selected safety threshold. If the path is clear, the controller can continue forward; if the path is blocked, it stops forward movement, compares the available scan directions and turns toward the direction with greater clearance. This is a reactive method based on current measurements rather than a persistent map of the environment.

Metal detection is checked as part of the repeated control process. A positive detector output produces an audible indication from the module and a corresponding LCD message. Meanwhile, the camera subsystem initializes its image sensor, connects to the local Wi-Fi network and serves the video stream independently of the movement-control loop.

4.1. Subsystem Integration

Integration follows a staged process so that faults can be isolated more easily. The battery polarity and converter output are checked first. The main controller and LCD are then verified, followed by the ultrasonic sensor and servo. The motor driver and geared motors are tested after the sensing functions are available. The metal detector is connected and checked next, and the camera stream is configured as a separate final subsystem. After each stage, the relevant function is checked before moving to the next stage.

4.2. Operating Cycle

During integration, the controller and the motor driver should be checked together because the control signal and the motor-current path perform different roles. The ESP32 supplies the logic commands, while the driver switches the current required by the motors. The shared ground provides a common reference for the connected electronics. If the robot behaves unexpectedly during a test, checking the supply, wiring and control outputs in a step-by-step manner can help locate the source of the problem.

During a normal operating cycle, the ultrasonic sensor is directed toward a selected scan position and returns an echo signal after transmitting a pulse. The controller uses the echo duration to estimate the distance to an obstacle. If the measured path is considered clear, forward motion can continue. If the distance is below the selected safety threshold, the robot stops and evaluates alternative directions. At the same time, the controller checks the metal-detector signal and updates the local display when required.

The control and video paths operate concurrently but have different responsibilities. The main controller reads sensor inputs and generates movement commands, while the camera subsystem captures and transmits image frames. The camera is not used to make obstacle-avoidance decisions in the current implementation. Consequently, the robot's immediate movement response is based on ultrasonic measurements, and the video stream serves as a visual aid for the remote operator.

5. Results and Discussion

The supplied project report records successful operation of the principal subsystems during the reported tests: ultrasonic measurements over the stated approximate 2–400 cm range, stable local video streaming, detection responses to ferrous and non-ferrous test samples within the effective detector range, and no observed controller resets during the described motor trials. These observations demonstrate functional integration of sensing, movement, local feedback and visual monitoring. They should not be interpreted as quantified accuracy or reliability statistics because the report does not provide a full test dataset, repeated-trial counts or measured detection probabilities. The assembled prototype is shown in Fig. 2.

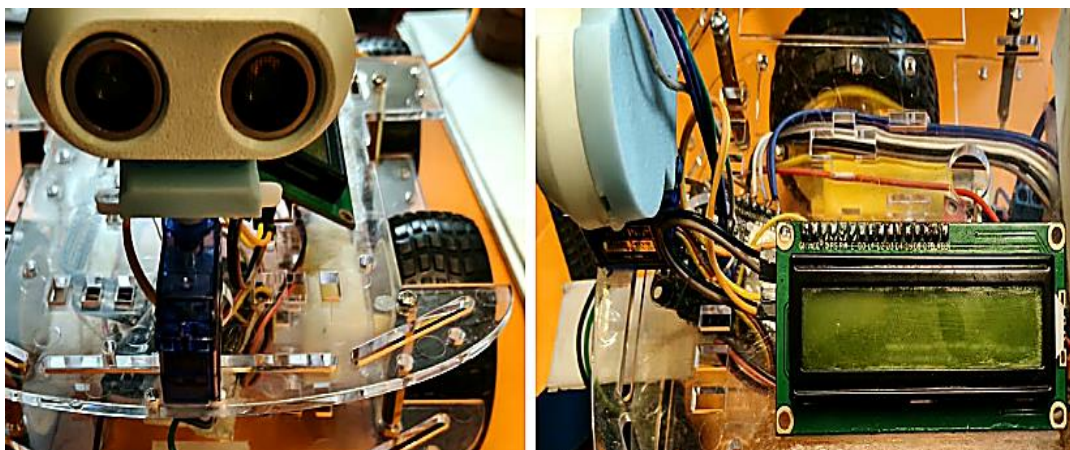


Fig. 2. Hardware prototype of the surveillance robot (photographs from the supplied project report).

The reported trials support the functional integration of the principal subsystems: the robot obtained ultrasonic distance readings, streamed video on the local network, responded to ferrous and non-ferrous test samples, and operated during the described motor trials without observed controller resets. These observations show that the sensing, movement, local feedback and visual-monitoring functions could operate together in the prototype.

The available report does not provide a complete dataset, repeated-trial counts or measured detection probabilities. Therefore, the observations should be treated as functional test results rather than quantified accuracy or reliability statistics. More systematic trials under different lighting, obstacle shapes, target materials, distances and battery conditions would be needed to characterize performance.

5.1. Practical Limitations

Ultrasonic sensing may miss narrow, angled or poorly reflecting objects, and the servo scan samples only selected directions rather than building a continuous map. Metal-detector response depends on target properties and distance. The Wi-Fi video stream is intended for a local network and depends on network availability. The prototype does not include GPS, autonomous mapping, cloud logging, AI-based object classification or a certified mine-detection mechanism.

The obstacle-avoidance method samples selected directions and cannot represent the surroundings as a continuous map. Narrow objects, angled surfaces and poorly reflecting targets may produce missed ultrasonic detections. The metal detector's response varies with target size, material, orientation, distance and nearby interference. In addition, the local video stream depends on Wi-Fi availability, and the prototype is not intended to replace certified industrial, military or mine-clearance equipment.

5.2. Interpretation of the Results

The prototype combines three forms of system response: movement in response to distance measurements, a local alert when metal is detected, and visual information from the camera. These responses support a basic inspection workflow in which the operator can observe the environment while the robot reacts to nearby obstacles. The functions are complementary, but they do not provide a complete understanding of the environment. The camera stream is not currently used for automated decisions, and the detector does not identify the type of metal.

The reported observations indicate that the main functions were integrated successfully at prototype level: distance sensing, obstacle response, metal indication, LCD feedback and local video streaming. The separation between motion control and camera operation is a useful feature because visual monitoring can continue while the main controller responds to sensor inputs. However, the available test description does not provide enough repeated measurements to calculate numerical accuracy, detection probability or long-term reliability.

5.3. Suggested Further Testing

Reliability testing should consider repeated startup and shutdown cycles, since initialization is required for the controller, display, servo, sensor interfaces and camera stream. The motor outputs should remain in a safe state during startup. The camera stream should be checked after the main controller has initialized, and the robot should be observed for unexpected resets when the motors start or change direction. Any failure should be recorded with the test conditions so that the same situation can be reproduced.

The robot should be evaluated on a flat, open test surface before being used in a more cluttered area. The ultrasonic sensor should be checked at several scan positions, and the servo should be allowed to settle before a distance measurement when necessary. The safe-distance threshold should be selected with the robot's movement speed in mind. These precautions improve the consistency of a demonstration but cannot guarantee detection of every obstacle. A test log should include the date of the test, the battery condition, the surface on which the robot travelled, the obstacle position, the measured distance, the movement response and any observed interruption in video. Keeping the same record format across trials would make it easier to compare results after code or wiring changes. It would also help separate faults caused by a particular subsystem from issues that occur only when all subsystems are operating together.

A more detailed evaluation could record the actual distance and displayed distance for several obstacle positions, the number of successful obstacle-

avoidance attempts, the response to different metallic samples and the stability of the video stream at different locations within the local network. Tests could also be repeated at different battery-charge levels. Recording the number of trials and the number of successful responses would provide a clearer basis for comparing performance after future modifications.

For obstacle testing, objects can be placed at measured distances in front of the robot and at different angles to the sensor. Each trial can record whether the distance was detected, whether the robot stopped in time, and whether the selected turn provided a clear path. Repeating the same arrangement several times would help distinguish a consistent response from an occasional successful result. Such tests should be conducted at a controlled, moderate speed and with enough open space for turning.

Metal-detection testing can use representative samples such as a steel screw, a nail, aluminium foil and copper wire, as described in the project report. For each sample, the approximate distance, orientation and detector response can be noted. Since response varies with target properties and coil geometry, the results should be reported as observations for the tested conditions rather than as a universal detection range. Nearby metal structures should also be considered because they may affect the response.

Video testing can include checking whether the stream starts correctly, remains visible on the local Wi-Fi network and provides useful images under the intended lighting conditions. The operator can note any interruption or delay observed during the trial. Power testing can record the regulated output before and during motor operation, because motor startup current may influence supply stability. These records would provide practical evidence for deciding which subsystem needs improvement first.

6. Applications and Future Scope

Potential educational and experimental applications include remote inspection of confined spaces, laboratory demonstrations of embedded control, basic security observation, obstacle-avoidance experiments and preliminary metal-object screening. It is not designed to replace certified industrial, military or mine-clearance equipment.

Future improvements could include a more robust wireless command interface, battery monitoring and protection, improved chassis wiring, measured range and reliability testing, a more capable obstacle-mapping sensor, cloud-based event logging and image-processing algorithms. A future version could also record test results systematically to quantify camera performance, obstacle-avoidance success and metal-detector sensitivity.

The modular design is suitable for educational demonstrations involving embedded programming, sensor interfacing, motor control, wireless video communication and power regulation. It can also be used for controlled experiments in remote observation, obstacle avoidance and preliminary screening for metallic objects in locations that are inconvenient to inspect directly.

Further development may include battery-voltage monitoring and protection, improved chassis wiring, a more capable obstacle-mapping sensor, cloud-based event logging and image-processing algorithms. Additional testing should record obstacle-avoidance success, video performance and metal-detector sensitivity across repeated trials. These are proposed extensions and are not features claimed for the current implementation.

6.1. Maintenance and Improvement Considerations

The lithium-ion battery arrangement requires careful handling. The two cells form a nominal 7.4 V source, and the buck converter provides the regulated 5 V supply described for the prototype. Battery condition, converter current capability and wiring quality influence practical operation. The cells should be used with suitable charging and protection practices, and the power arrangement should not be treated as a certified battery-management system.

A pre-operation checklist can include checking the battery polarity, confirming the regulated output, inspecting the common ground, securing the motor terminals, and verifying that the LCD and camera start correctly. The robot should be switched off before changing wiring. The metal detector should be tested with a known sample, and the ultrasonic sensor should have an unobstructed view. A short functional check of each subsystem can reduce avoidable interruptions during the final demonstration.

Before each demonstration, the battery connections, common ground, motor wiring and regulated output should be checked. The sensor should have a clear view of the area being measured, and the metal detector should be tested with representative samples. The robot should be operated in a controlled environment with adequate space to turn. These checks help make demonstrations more repeatable, although they do not remove the sensing limitations of the present design.

6.2. Future Development Priorities

A useful future evaluation would compare the present design with any proposed upgrade using the same test conditions. For example, a revised obstacle sensor could be evaluated by recording detection and avoidance outcomes for the same set of obstacle positions. A revised camera program could be evaluated by recording stream availability and interruptions on the same local network. This approach would help show whether an upgrade produces a measurable improvement rather than merely adding complexity.

Future development should retain the modular approach used in the present design. A change to the sensing system can first be evaluated with the existing controller and display, while a software improvement to the camera can be tested without altering the motor-control logic. This staged approach helps maintain a clear relationship between each change and its effect. Performance should be documented through repeated trials rather than relying only on a single successful demonstration.

Future work can be prioritized in stages. First, battery monitoring and protection can improve power-system awareness. Second, repeated tests can be used to quantify the current sensing and movement performance. Third, a more capable ranging or mapping sensor could improve environmental awareness. Finally, image-processing methods and event logging could be explored as extensions. These improvements are proposed possibilities and are not part of the current prototype.

A future version could provide a more robust remote command interface and a structured record of detection events. Battery monitoring would help the operator understand the remaining power state, while improved wiring and suitable battery protection would support safer repeated demonstrations. A more capable ranging sensor could provide a richer representation of the environment than a few ultrasonic scan points. These upgrades should be evaluated individually before combining them, so that their effect on system performance can be identified.

Image processing is another possible extension, but it would require additional implementation and testing beyond simple video streaming. A future system could investigate identifying selected objects in the camera image or saving event information for later review. Such functions should be treated as future work because the present prototype provides visual monitoring and does not claim advanced image recognition, cloud recording or image-based autonomous navigation.

7. Conclusion

The current system is best understood as an educational prototype for demonstrating the interaction of sensors, embedded control, motor actuation and wireless visual feedback. It offers a foundation for further work in obstacle response, remote inspection and preliminary metallic-object screening. Its limitations, particularly the sampled nature of ultrasonic scanning and the variable response of inductive detection, should remain clear when describing its intended applications.

A low-cost mobile surveillance robot integrating an ESP32 DevKitC, ESP32-S3 infrared-capable camera, servo-scanned HC-SR04 ultrasonic sensor, L298N motor driver, TT geared motors, A88 inductive metal detector and 16×2 I2C LCD has been described. The architecture separates motion control from video streaming and combines remote visual monitoring with local obstacle response and metal-detection alerts. Results reported in the project document indicate that the major subsystems operated together during prototype testing. The system is suitable as an educational proof of concept, while further quantified testing and hardware refinement are required before use in demanding real-world environments.

The project demonstrates a modular approach to combining remote visual awareness with local sensing and movement response. Separating the camera stream from the main control loop allows the robot to continue evaluating sensor inputs while video is being transmitted. The prototype therefore serves as an educational proof of concept for integrated embedded control, with further measurement and refinement required before considering more demanding real-world use.

Overall, the project brings together embedded control, wireless communication, sensing and actuation in a compact mobile platform. Its main contribution is the integration of these functions into a single demonstrable system with separate motion-control and camera tasks. The reported results support operation of the principal subsystems, while the absence of a complete repeated-trial dataset limits quantitative conclusions. Further controlled testing and incremental refinement are therefore appropriate next steps.

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