

Design and Development of an Intelligent Quadruped Robot for Real-Time Surveillance, Intrusion Detection, and Autonomous Patrolling

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Abstract

The use of human operators for surveillance purposes in large and difficult-to-reach locations poses unnecessary risks and requires constant attention. This paper introduces a design and construction of an intelligent quadrupedal robot for real-time surveillance, registration of intrusions, and autonomous patrol operation. The prototype of the proposed robot features four legs and an ESP32 microcontroller. With gun is mound on top of it A GoPro camera provides video surveillance, while a radar sensor connected to an ESP32 controller gives necessary obstacle and motion detection functions. To carry out simple monitoring of the operation of the robot, this robot is equipped with a temperature sensor. The robot is powered by a lithium battery and is capable of both teleoperated and autonomous patrol operation using wireless communication equipment. With the size of about 30×15 cm and weight of around 2 kg, this robot is designed to work in controlled surveillance environments. The experiments conducted will evaluate the following properties: motion capabilities, autonomous patrolling, evidence-gathering ability, communication ability, battery lifespan, and emergency stop ability. The findings will allow researchers to assess the viability of a straightforward and low-cost quadruped robot for security inspections and surveillance. The design of this technology presents a number of features, such as human The prototype is intended as a non-weaponized surveillance and inspection system and does not include a functioning weapon or destructive payload

Keywords: Intelligent robot; quadruped robot; security surveillance; air gun ,intrusion detection; autonomous patrolling; ESP32; GoPro camera; radar sensing; teleoperation; fail-safe control

1. Introduction

1.1 Background

Security monitoring could be useful in locations that are comparatively large, isolated, dangerous or challenging for humans to watch over continuously. Some examples of such locations include factories, warehouses, construction sites, campuses, agricultural fields, and other such sites. A mobile surveillance robot can help human operators by video capturing, scanning the vicinity, following mapped-out paths, and transmitting security alerts. This approach allows reducing the frequency of physical patrols while retaining the operator's position of the one who is responsible for taking the key decisions in the situations of need.

Quadrupeds can be useful in the above-discussed area due to their four-legged construction that enables them to be mobile in the area where a little wheeled car may have problems. Additionally, quadruped machines can also be designed as compact systems due to their indoor and outdoor applications. Previous experiments with quadruped robots included the combination of four-legged motion ability and good-quality video recording systems, motion detectors, object recognition software programs, and video transmission equipment. It is known that these systems are capable of using the quadrupeds-robot technology as moving surveillance platforms; however, it still depends on constant sensing, walking, transmitting, and controlling technology

1.2 sensing challenges

A camera serves as an important sensor for surveillance because it conveys visual information that can either be checked by a person or processed by an object recognition software. Unfortunately, camera efficiency may be affected by darkness, glare, dirt, smoke or fog, as well as by obstacles obstructing the camera's sight. Therefore, the second type of sensor can serve as a means of enhancing the robot's understanding of the environment.

Millimeter-wave radar is a potential complementary sensor for mobile robots. A review of applications of radar in the field of robotics states that radar is useful for estimating motion, localization and mapping, as well as detecting and classifying objects. It is worth mentioning that radar can provide data in conditions when visual sensors fail, due to its long wavelength allowing it to penetrate some type of fog, dirt and smoke. The aim of this project is to use the radar system to detect obstacles and movements and use the camera for visual monitoring. A combination of two sensors can potentially form a more efficient surveillance system as compared to using a camera alone.

1.3 Need for secure and safe autonomy

A connected surveillance robot is subject to mechanical and environmental failures as well as flaws in communication and cyber threats. Many robotic platforms experience unauthorized commands given by external sources, faulty sensors, interrupted communication, or compromising attacks on control software. As stated in the review of robotic platforms security, both cyber threats and physical threats are regarded as the most serious issues related to robot operation in mission-critical settings. Consequently, security robots should possess mechanisms for authentication, secured communication, operator override feature, activity logging as well as protocol for responding to suspicious or uncertain commands. Safe-area movement can also be accomplished if a safety mechanism is in place. The robot should not be moving on its own if communication is lost, a sensor fails, or contradictory information has been provided. Emergency stop mechanism should be designed with caution because cutting power may lead to instability and even falling of the robot. The recent research on safe stoppability suggests that robots should have a fallback control algorithm to maintain the balance and move to the state of minimal risks. Therefore, the proposed robot should incorporate stop servo system, take a stable position, activate the emergency stop mode,

1.4 problem statement

Numerous small prototypes of surveillance robots target a single objective like video surveillance, navigation via remote control, or avoiding obstacles. The surveillance platform utilized for security monitoring needs a combination of these objectives while ensuring affordability, size, ease of control, and safety. The primary engineering issue addressed in this article involves the construction of a mini quadruped robot that can manage real-time questioning and autonomous patrols based on the ESP32 control system, GoPro camera, radar aid for sensing, wireless connections, and servo motor locomotion.

Moreover, the prototype needs to work in the manual and autonomous control modes. The manual mode allows an authorized operator to check the location and intervene if needed while the autonomous mode implies that the robot follows a specific route. The transition between these modes has to be perfectly clear in a way that the operator can switch to the manual mode when the robot recognises any situation as dangerous or the performance of the autonomous system is not satisfactory.

2. Related Work

2.1 Quadruped Robot for Surveillance

Research has focused on robots for tasks such as monitoring, inspection and security surveillance. A quadrupedal platform works quite well when the robot navigates confined spaces, uneven terrain, or during conditions where wheeled motion is difficult. Owoseye et al. developed a quadrupedal home-surveillance robot equipped with high-res cameras, motion detectors, and object-recognition software. The intention behind this development was to enable detection of intruders and monitoring of the movements as well as streaming video in real-time. The work is quite pertinent to the current project since it provides a combination of a four-legged robot and a video/security application.

Other studies in the field of surveillance robots have suggested their use in autonomous patrol monitoring and risk detection. HERMES has been developed as an autonomous surveillance mobile robot for security patrol. This can serve as a reference for the design of a patrol-oriented system. The latest study on quadruped robots implemented a risk-detection system based on WebRTC and ROS2, which makes it possible to separate the functions of the robot control, video communication and risk detection. This implies that a surveillance robot should be considered not only as a moving camera but also

2.2 Autonomous navigation and mapping

Autonomous patrols require the robot to determine its position, plan its route, move around obstacles, and find a way out when it gets stuck. SLAM (simultaneous localization and mapping) is commonly used in autonomous surveillance machines to carry out mapping and navigation. Research has been carried out on obstacle detection in robots with four legs as part of their autonomous navigation. These studies are the path to make the machine operate in patrol mode.

The navigation question is rather tough for a small prototype since it is connected with the accuracy of actuators, the efficiency of batteries, the range of sensors, the power of the processor, and the effectiveness of wireless communication. If the robot can navigate successfully in a laboratory, it may fail in an unruly or dynamic environment. Thus, the project should focus on the description of the test environment, distance of patrol, completion rate, distance of cleaning, and cases of failures rather than just the patrolling technique.

2.3 Camera-based surveillance and intrusion detection

Camera systems provide valuable information for surveillance, as they can record colors, shapes, movements, and scene context. A high-resolution camera can enable remote observation and future review of recorded events. Nevertheless, image quality varies depending on the light conditions, camera angle, image blur, vantage point, and environmental obstructions. Therefore, the intrusion-detection system based on camera technology must determine the criteria for intrusion event detection. For instance, this may include humans entering restricted premises, unexpected obstructions on the patrol route, or any movements taking place in the monitored area during the specified monitoring time.

This project proposes the use of a GoPro camera for visual observation. The exact parameters of the camera in terms of resolution, frames per second, field of vision, and video transmission should be outlined

in the hardware and methodology sections. In addition, if the detection of contact is performed by a separate computer or operator and not directly by ESP32, this should be explicitly stated as well. It should also be mentioned that ESP32 may provide coordination for control and communication purposes but may have problems with advanced image processing due to limited computing capabilities.

2.4 Radar sensing for robotic perception

Other relevant research studied radar systems in terms of navigation and obstacle detection. Research has also been carried out regarding the manner of using radar sensors in autonomous robots for navigation. Radar imaging has also been extensively studied for infantry vehicles for navigation and monitoring that include obstacle detection that could not be seen due to vegetation and foliage. Thus, these results demonstrate that radar can be utilized as a source of data about the surrounding environment; however, radar parameters must be understood according to the peculiarities of the specific radar operating range, range resolution, and sensitivity to reflection.

In the project to be proposed, the project involves using an ESP32 radar device. Since the terminology of “ESP32 radar” doesn’t specify the radar device, it is necessary to specify the radar sensor type and operating frequency before finalizing the paper. The paper must also make the distinction between the ESP32 controller and the radar system in terms of hardware involved in the radar experiment. The parameters that should be evaluated in this paper are the detection distance, false positive detections, effectiveness of the system with static and moving objects, and efficiency of the radar system in different lighting

2.5 Sensor fusion

The use of several sensors can enhance reliability when they provide complementary data. In particular, the camera can serve the purpose of giving visual evidence, while the radar indicates distance and movement. An easy method of fusing data could compare the camera readings and radar signals originating in the same area. A more complicated approach could imply the common coordinate system where obtained values would be combined, whereas an even more sophisticated approach would involve the use of probabilistic tracking.

Research in the area demonstrates that radar-camera systems need to be appropriately calibrated, equipped with synchronization, and processed adequately. This is why the prototype discussed in the present work must fix the locations of the camera and the radar, define the relationship between recorded measurements, and explain how the combined outputs were calculated. The study must not suggest that sensor fusion entails improvement unless tests comparing camera and camera plus radar outputs in identical situations were done.

2.6 Fail-safe control and emergency stopping

Whenever a surveillance robot experiences a failure in sensors, communication, control, or any of its actuators, it must have a fallback protocol. Traditional approach in emergency systems is to cut power. However, power cutting may not be a solution since it may result in a loss of balance of the robot. Safe Stoppability project deals with the concept of emergency stopping in terms of State Machines that allow moving a robot into a safer position instead of stopping it unprepared. Previous studies have addressed contact and stoppage issues of human-robot coexistence.

Thus, the quadruped being designed should implement different stop mechanisms. Regular operator stop can be embodied in immediate stopping of robot walking and remaining stationary. Dangerous situation stop can command to have the robot in sitting position, stop it from moving autonomously, and wait for the operator to give permission for restarting the movement. Low battery situation may initiate the return

to the safe location if it is safe to do so. The paper will examine the parameters of emergency stop such as latency, stop position, and repeatability of actions.

3. System Requirements

This system is a smart robotic quadruped designed for security vigilance, remote monitoring, autonomous functionality, and danger identification. This robot was created to function in indoor and outdoor controlled surroundings, and it has remote-controlled as well as future autonomous functioning ability. The key requirements of the system are split into hardware, sensing, communication, control, security and safety requirements.

Defensive Payload Module: The robot platform includes a mounted defensive payload as part of the proposed security concept. The payload is intended to remain under authorized operator control and is treated as a separate subsystem from the robot's navigation and surveillance functions. The research focuses on the integration, safety interlocking, authorization, and fail-safe behavior of the overall robotic platform rather than weapon operation.

3.1 Hardware Requirement

The robot will have a framework that is designed to be used in four legs. The legs will be equipped with various servo motors that will help in achieving stable quadrupedal locomotion. To accomplish this, a microcontroller, such as ESP32, will be used in the design structure to manage movement, provide sensor information, perform communication tasks, and maintain security for the entire operation of the device.

The working operation of the robot will be based on the 12V power source with efficient power supply on the components like ESP32, sensors, servo motors, as well as the electronic subsystems for operation and functioning of the machine.

1 Component Details

The proposed security robot consists of several integrated hardware components that work together to provide locomotion, sensing, surveillance, communication, power management, and fail-safe operation.

Sr. No.	Component	Quantity	Function / Purpose
1	ESP32 Microcontroller	2	Main controllers for robot-side and remote-side control, sensing, communication, and safety logic
2	Servo Motors	12	Quadruped leg movement and posture control
3	Ultrasonic Sensor	1	Short-range obstacle and distance detection
4	High-Resolution Camera	1	Real-time visual surveillance
5	Radar Module	1	Object and movement detection; radar information is shown on the remote display
6	RF Transmitter/RC Controller	1	Wireless remote control of the robot
7	RF Receiver	1	Receives commands from the RC controller
8	Remote Display	1	Displays radar information to the operator
9	12 V Battery	1	Main power source for the robotic system
10	5 V Relay Module	2	Isolated switching interfaces for separate security-related subsystems

11	High-Voltage Converter	1	Provides the required higher-voltage supply for the connected high-voltage subsystem through the relay interface
12	Mounted Defensive Payload	1	Separate authorized security payload integrated into the robot architecture
13	Fail-Safe Control System	1	Automatically stops the robot when RC communication is lost

3.2 Sensing and surveillance Requirement

A system that uses ultrasound technology will be put into place for determining the distance to obstacles and for short-distance awareness of the environment. The ultrasound technology will be working at all times, measuring the distance to different objects and reporting the measurement results to the robot's controller.

A camera that works with high resolution will be included in the design for ensuring the process of real-time observation. The camera will send the operator the video information that enables monitoring of the surroundings.

There are plans to add a radar-based sensing component in the future to allow for better motion and environment detection abilities. Overall, the combination of all three systems, that are infrared, ultrasonic, and radar, will advance the situation awareness capabilities of the robot.

3.3 Control and Communication Requirement

The robot must provide remote control functionality via an RF RC controller. The controller must enable the authorized operator to steer the robot and keep track of its activity.

All commands from the remote control must be processed by the ESP32 which must send appropriate commands to the robot's actuators.

The communication system must include a reliable mechanism for connection loss detection. If the communication with the remote controller is lost, the robot must stop working and go to a safe mode.

3.4 Security and Threat-Response Requirement

The robot will have a mobile security and surveillance system which can provide information to the operator and recognize abnormal movements.

Further upgrades might contain new protective modules that are designed to act as controlled security functions, and be limited to operating under certain conditions. This prototype will mostly focus on security, surveillance and detecting threats.

The robot can incorporate systems to detect tampering and disable it when robbery happens so that there will be no chance of it being used against people.

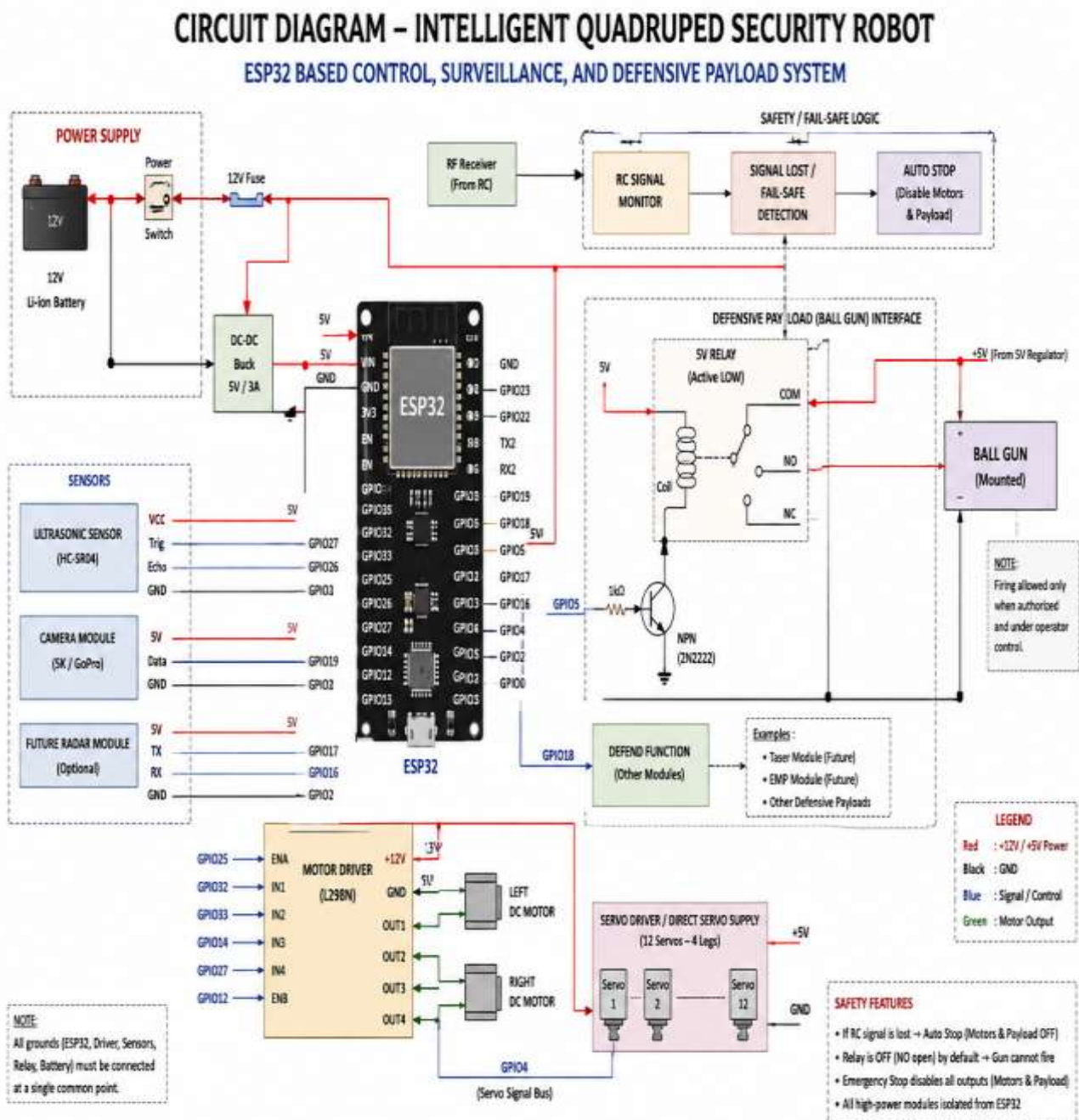
3.5 Functional Requirement

The developed prototype shall satisfy the following major functions:

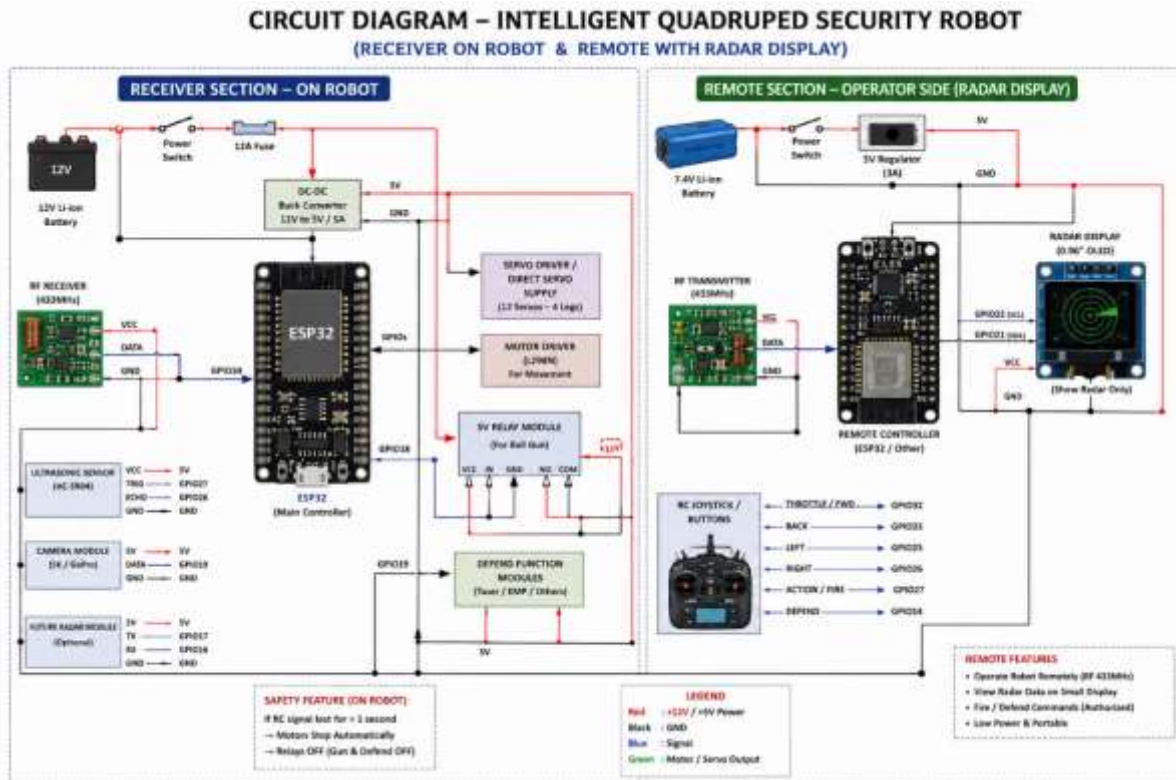
- Four-legged robotic locomotion.
- ESP32-based central control.
- Ultrasonic obstacle-distance detection.
- Camera-based real-time surveillance.
- RF RC-based remote operation.
- Real-time operator control.
- Communication-loss detection.

- Automatic movement stop when the RC connection is lost.
- Security and intrusion-monitoring capability.
- Provision for future radar integration.
- Provision for future autonomous patrol operation.
- Provision for additional controlled security-response modules.
- Safe shutdown and fail-safe operation during abnormal conditions.

4. Circuit diagram



Receiver



5. Proposed Methodology

The outlined approach entails the design, creation, integration and examination of a miniaturized quadrupedal robot, controlled by ESP32, meant for surveillance and monitoring from a distance. The work can be categorized into mechanical, communication, sensing, control and surveillance subsystems.

5.1 Mechanical and locomotion System

The robot utilizes a quad legged robot design. The composition of each leg consists of multiple servo motors to provide joints' movements required for standing and walking. The movement system is controlled using the ESP32, which communicates with the RF-based remote control and identifies commands for servomechanisms to operate.

In terms of the mechanical structure, the design maintains balance during motion while allowing room for controller and powering feed and tools such as camera, communication method, and others.

The ESP32 microcontroller serves as the main controller of the robot. It manages movement of the robot as well as sensor data ingestion and other processes related to communication and surveillance.

5.2 RF-RC system

The robot is remotely controlled via RF based remote control unit. The signaling is picked by robot's RF receiver and transferred to ESP32 system that controls the robot. The operator controls movements of a robot via the remote control unit and can intervene if need be.

The remote unit has a small screen that will be used to display radar data in the future. The radar data, sent to the remote unit from the robot, would be processed by the remote system and presented to the operator as a distance and obstacles information giving the operator the ability to see the surroundings.

5.3 Security and Defensive Payload Integration

A gun is included in the robotic base as a specific type of weapon within the suggested security architect-

ure. The weapon is regarded as a valid subsystem independent of the functions of locomotion and surveillance. The proposed method presumes integrated system-level methodology in the aspects of authorization, safety interlocking and fail-safe behavior rather than weapon operation.

It is also planned to implement several security-response modules in future versions of the platform. The newly designed modules will be functioning under authorized operating conditions and will be still independent of autonomous navigation and regular surveillance function.

5.4 Communication-Loss and Fail-Safe Method

The robot constantly checks the communication pathway to the RC controller. The ongoing stream of electronic signals is used to check if the connection with the controller is still functioning. If the connection gets disconnected, the ESP32 will give the command to the robot to come to a halt and to go into a safe state.

The fail-safe mechanism has been purposely developed to prevent the robot from moving unintentionally in the absence of any communication. The system will keep the safety payloads turned off through communication malfunctioning and will demand the re-establishment of an authorized communication connection for normal functioning.

6. Results

The developed quadruped robot was tested under controlled conditions to evaluate its basic locomotion, sensing, surveillance, communication, safety, and power-performance characteristics. The prototype successfully demonstrated four-legged movement and remote operation through the RF-based RC controller.

6.1 Locomotion and Obstacle Detection

The quadruped locomotion system operated successfully during the conducted tests. The ultrasonic sensing system was able to detect nearby obstacles with a measured range of approximately **400 cm (4 m)** under the test conditions. The sensor provided distance information to the ESP32 for environmental awareness and obstacle identification.

6.2 Surveillance and Radar System

The high-resolution camera system operated successfully and provided visual surveillance of the robot's surroundings. The radar module was also integrated into the prototype, and a small display was installed in the remote unit specifically for presenting radar information to the operator. The remote display provides a dedicated interface for observing radar-based distance and object information.

6.3 RF Communication and Remote Operation

The RF-based RC control system successfully provided remote control of the robot. During testing, the effective tested communication distance was approximately **5 m**. The system allowed the operator to control the robot while maintaining a wireless connection between the remote controller and the robot.

6.4 Fail-Safe Operation

The communication-loss safety function was successfully demonstrated. When the remote-control connection was disconnected, the robot automatically stopped its movement and entered the predefined safe state. This confirms the operation of the communication-loss detection and automatic stopping mechanism described in the proposed methodology.

6.5 Security Payload Integration

The prototype includes a mounted defensive payload as part of the overall security-robot architecture. The payload is integrated as a separate subsystem with the robot's control and safety architecture. Testing of

the research prototype focused on system-level integration and safe control behavior rather than operational weapon performance.

6.6 Battery Performance

The 12 V battery-powered system achieved an observed operating duration of approximately **80 minutes** under the tested operating conditions. Actual operating time may vary depending on walking activity, servo load, camera operation, communication activity, and other connected modules.

6.7 Overall Result

The experimental results demonstrate that the developed prototype can perform the intended basic functions of a remotely operated quadruped security platform, including locomotion, ultrasonic obstacle detection, camera surveillance, radar-based monitoring, RF communication, automatic stopping after communication loss, and extended battery-powered operation. No major operational problems were reported during the stated tests. The results indicate that the prototype provides a suitable foundation for further development of autonomous patrol, advanced sensor fusion, and additional security functions

7. LIMITATIONS

The developed quadruped security robot has several drawbacks at the present prototype stage of development. First, the system has been primarily designed for working in controlled environments, and its RF communication range is about 5 m, which limits the robot's capability of working over long distances. In addition, the range of the ultrasonic sensor is about 400 cm, and its efficiency depends on such characteristics as object's size, shape, and surface. The robot is controlled manually at the moment, while autonomous navigation and patrols will be implemented in the future. Furthermore, the camera and radar systems might be influenced by external environmental factors and should be tested under other operating conditions. The battery life time in the prototype is about 80 minutes and it is likely to depend on various factors, including servo movement, sensing, camera use, communication, and payload carrying. Integration of other security payloads is another factor increasing the system complexity, and it is necessary to provide some security and authorization measures.

8. Conclusion

The developed intelligent quadruped robot shows that it is possible to use a small ESP32-based robotic platform for security surveillance and remote monitoring. The robot includes four-legged movement capability, ultrasonic obstacle detection, camera surveillance, radar surveillance, RF remote control, remote display of radar surveillance results, and a safety stop upon losing contact with the control station. The prototype resulted in the achieved ultrasonic obstacle detection distance of about 400 cm, RF remote control distance of about 5 m, and battery working time of about 80 minutes under experimental conditions. The security payload is included in the robot as a separate subsystem with focus on authorized control and fail-safe operation. While at the current stage of development the prototype is mainly targeted to controlled environment and manual control, it represents a base for further research on autonomous patrol, sensor fusion, remote control over greater distance, better environmental perception, and power consumption improvement. Therefore, the proposed robot can be used as a promising base for further research and development of intelligent robotic security and surveillance systems.

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