Design of a Dual-Mode Quadruped Robot for Explosive and Narcotics Detection in Railway Environments

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Abstract — Railway security teams use patrols, CCTV surveillance, baggage screening and trained dogs to identify suspicious activity and hazardous materials where inspection still depends largely on personnel and equipment placed at specific locations. This limits the examination across coaches, platforms, yards and track-side areas using one mobile system. This paper presents the design of a dual-mode quadruped robot intended to assist security personnel in these inspections. The proposed system brings together Spatially Offset Raman Spectroscopy (SORS) for checking liquid containers, Terahertz (THz) imaging for concealed materials, Ion Mobility Spectrometry (IMS) for chemical-vapour detection, Ground Penetrating Radar (GPR) for track-bed inspection and Pulse Induction Metal Detection (PIMD) for metallic objects. An NVIDIA Jetson Orin Nano handles perception and mapping, while an STM32 controller manages balance and movement. The platform supports an IP65-rated aluminium sub-chassis, electromagnetic-interference protection and copper heat pipes for thermal management. 4G LTE is the primary communication link, with LoRa as backup available when cellular service is lost. Sensor data can be stored on a one TB NVMe drive until the primary communication returns. A hardware emergency interlock is included for robot safety and maintain system integrity.

Key Words: Quadruped Robotics, Railways Security, Explosive and IED Detection, RPF Patrol Automation, Multi-Spectral Chemical Sensing, Embedded Control with Active Thermal Management.

1. INTRODUCTION

Railway network operates a large and geographically distributed transportation network consisting of stations, platforms, train coaches, yards, and track infrastructure. The Railway Protection Force (RPF) is responsible for safeguarding railway property, passengers, and associated infrastructure [2]. However, threats such as illegal drug transportation and the presence of improvised explosive devices (IEDs) can create serious risks for railway operations and passenger safety. The SIH 2026 problem statement reports that RPF recovered narcotic substances worth approximately ₹300 crore across more than 2,100 instances in 2025 and cites NCB data indicating that a portion of drug trafficking is routed through the railway network [1].

Existing railway security systems primarily rely on fixed screening equipment and human patrols. These approaches do not provide a single mobile platform capable of inspecting coaches, station areas, railyards, and under-carriage regions. Conventional screening generally uses fixed X-ray systems, metal detectors, and manual security patrols. Such fixed screening arrangements do not provide the mobility required for inspection across narrow coach spaces, railway yards, and track-bed areas where concealed objects may be present. Commercial quadruped robots such as Spot demonstrate the feasibility of quadrupedal robotic platforms for mobile inspection applications [14]. The railway environment considered in this work can expose the robot to high ambient and track temperatures.

To address these requirements, this study presents the design and system architecture of an indigenous dual-mode quadruped robotic platform for railway security applications. The proposed platform combines multiple sensing technologies for chemical, explosive, metallic, and subsurface threat inspection with a quadrupedal chassis designed for demanding railway environments.

The primary contributions of this research include:

1. Integrated Hazard Detection Payload: The proposed platform combines multiple sensing methods for railway security inspection. Spatially Offset Raman Spectroscopy (SORS) is proposed for non-contact inspection of liquid containers [4], [5], while Terahertz (THz) imaging is intended for detecting concealed or subsurface materials [8],[9]. Ion Mobility Spectrometry (IMS) is used for chemical-vapor analysis [6] [7], Ground Penetrating Radar (GPR) supports track-bed inspection [10], and Mu-Metal-shielded Pulse Induction Metal Detection (PIMD) is used to identify metallic objects [11].

2. Two-Level Computing Architecture: The computing system separates high-level perception from low-level motion control. The NVIDIA Jetson Orin Nano performs YOLO v8/v10 inference and other perception tasks [3] [17] [18], while the STM32 micro -controller handles inverse kinematics and gait balance calculations at a target frequency of 500 Hz using bare-metal C++.

3. Thermal and EMI Protection: The robot uses an IP65-sealed 6061-T6 aluminium sub-chassis to provide mechanical protection and electromagnetic shielding from the railway environment. A copper heat-pipe cooling arrangement is included for thermal management, while Aerogel insulation is used around the battery compartment to reduce heat transfer.

4. Communication Backup and Safety Interlock**:** The communication system is designed to use 4G LTE during normal operation and switch to an 868/915 MHz LoRa link when cellular connectivity is unavailable. Sensor and system data can be stored locally on a 1 TB NVMe SSD during communication loss. An optocoupled solid-state relay is also included to disconnect the motor power bus during an emergency stop condition.

2. HARDWARE REQUIREMENT

The hardware architecture of the proposed quadruped platform is designed for railway environments while supporting multiple sensing and processing functions. The system is divided into several subsystems covering computation, hazard sensing, navigation, communication, power management, and mechanical protection. The main hardware components are:

- **Computing Subsystem:**
  - **High-Level Processing Unit:** An NVIDIA Jetson Orin Nano 8 GB developer module which has inbuilt NVIDIA Ampere GPU and ARM-based CPU is used for high-level perception and computation [3]. It performs YOLO v8/v10 neural-network inference [17] [18], 3D point-cloud processing, and ROS 2-based robotic software integration [15].
  - **Low-Level Control Unit:** An STM32H7 microcontroller is responsible for low-level actuator control and balance processing. The controller receives IMU measurements and generates the required PWM signals for the actuator ESCs. The control loop is designed to operate at 500 Hz.
  - **Local Storage:** A 1 TB M.2 NVMe SSD is provided for storing sensor data, telemetry, and other system logs when network connectivity is unavailable.
- **Multi-Sensor Hazard Detection System:**
  - **Spatially Offset Raman Spectrometer (SORS):** A 785 nm Raman excitation source is considered for non-contact analysis of liquid contents through opaque containers [4], [5]. The optical assembly includes a protective sapphire window.
  - **Ion Mobility Spectrometry (IMS) Chemical Sniffer:** A compact IMS-based sensing unit is proposed for chemical-vapor analysis [6], [7]. A micro-vacuum pump draws sampled air through a hydrophobic PTFE membrane before the sample reaches the IMS drift region.
  - **Terahertz (THz) Imaging Unit:** A non-ionizing THz sensing array is proposed for examining concealed materials beneath or behind selected non-metallic surfaces [8], [9].
  - **Ground Penetrating Radar (GPR):** This sensor is proposed for scanning the railway track bed and identifying subsurface variations [10]. The operating frequency and effective scanning depth will be specified according to the selected GPR hardware.
  - **Pulse Induction Metal Detector (PIMD):** Two pulse-induction coils are proposed for detecting metallic objects [11]. Mu-Metal shielding is included as a proposed measure to reduce magnetic interference with nearby electronic components.
- **Perception, Navigation and Communication Modules:**
  - **3D Time-of-Flight LiDAR:** A solid-state ToF LiDAR unit is used to generate three-dimensional point-cloud data for navigation and environmental mapping around the robot.
  - **Doppler mmWave RADAR:** This radar unit is intended to support motion estimation and ground-speed measurement, while providing an additional sensing modality when optical visibility is reduced.
  - **RGB and Thermal Imaging:** A 4K RGB camera is combined with an uncooled long-wave infrared (LWIR) thermal sensor to support visual inspection and thermal-anomaly monitoring under different lighting conditions.
  - **Navigation and Communication:** A u-blox NEO-M10 GNSS receiver provides positioning information, while a Cat-4 4G LTE modem provides primary communication. A LoRa transceiver provides an alternative communication link when network connectivity is not available. The communication antennas are positioned outside the main shielded enclosure as a design measure to reduce potential signal attenuation.
- **Power Electronics, Safety Interlock and Enclosure:**
  - **Main Power Source:** The robot uses a 48 V LiFePO4 battery pack with a smart battery-management system. A 100 V low-ESR capacitor bank is included on the main power bus to reduce voltage disturbances caused by motor back-EMF.
  - **Voltage Regulation:** Two buck-converter stages provide regulated 12 V and 5 V power rails for the computing and logic circuits.
  - **Hardware Emergency Interlock:** An optocoupled solid-state relay (SSR) is used to isolate the 48 V motor power bus when an emergency-stop condition occurs.
  - **Structural Enclosure and Thermal Management:** The outer enclosure uses flame-retardant polycarbonate, while the inner structure consists of a 1.5 mm 6061-T6 aluminium chassis. The chassis provides environmental and electromagnetic protection. A CNC-machined aluminium cold plate with copper heat pipes is used for

processor cooling, and Aerogel insulation is provided around the battery compartment.

3. SOFTWARE REQUIREMENT

The software is divided into separate tasks so that low-level motor control can run independently from high-level vision processing and data communication. The main software components are:

- **High-Level Processing Unit (NVIDIA Jetson Orin Nano):**
  - **Operating System and Middleware:** Ubuntu Linux LTS is used with Robot Operating System 2 (ROS 2) for managing software nodes, exchanging messages between modules and handling robot actions [15].
  - **AI and Vision Pipeline:** CUDA and TensorRT are used to accelerate YOLO v8/v10 models on the Jetson platform [3], [17]-[19]. The vision pipeline can process RGB and thermal information to support object detection and monitoring of the surrounding environment.
  - **Spatial Mapping and SLAM:** ROS 2-based sensor fusion combines 3D ToF LiDAR data, mmWave radar measurements, and 9-axis IMU data for localization and mapping. Fast-LIO can be considered for LiDAR-inertial mapping while the robot moves along the railway environment [16].
- **Low-Level Control Software (STM32 MCU):**
  - **Execution Framework:** The STM32 runs a bare-metal C++ program without a general-purpose operating system. This allows the controller to execute the motor-control tasks directly.
  - **Kinematic Balance Loop:** The controller is designed to run a 500 Hz control loop using IMU feedback. It calculates inverse kinematics and updates the gait and actuator commands to maintain the robot's balance during movement.
- **Sensor Processing Libraries:**
  - **SORS Spectral Processing:** The software processes the Raman spectra obtained from the SORS sensor and compares the measured spectral features with stored reference data for material identification.
  - **IMS Signal Processing:** The software analyses the ion-mobility spectrum and uses the detected peak positions to identify possible chemical signatures and generate alerts when required.
- **Communications and Data Storage:**
  - **Online Communication:** MQTT and WebSockets can be used over the 4G LTE connection to transmit telemetry, GPS information, sensor data, and system status to both the remote controller and the railway monitoring dashboard.
  - **Offline Communication:** When the 4G connection is unavailable, the LoRa link can be used to send important alerts, telemetry, and system status to the remote controller or LoRa gateway [20]. Data that cannot be transmitted immediately can be stored locally on the 1 TB NVMe SSD for later synchronization with the monitoring system.
  - **Local Data Storage:** SQLite and the local file system are used to store sensor readings, telemetry, and event logs on the 1 TB NVMe SSD during offline operation. When the 4G connection is restored, the stored data can be synchronized with the remote monitoring system and railway dashboard.

4. LITERATURE REVIEW

Railway security inspection may involve fixed screening arrangements and manual inspection methods at designated locations. These approaches are useful for screening at specific locations, but they provide limited support for mobile inspection inside train coaches, along platforms, and in railway yards. Manual inspection may also require personnel to approach objects or substances before their nature has been established, creating an additional safety consideration during initial inspection.

Mobile robots have been investigated for inspection and security-related applications. Quadruped robots provide four-legged mobility that can support operation over uneven terrain and complex environments [12], [13]. Commercial platforms such as Boston Dynamics Spot also demonstrate the use of quadruped mobility with onboard sensing and computing capabilities [14]. For outdoor deployment, direct solar exposure and high ambient temperatures can increase the thermal burden on onboard computing hardware. Therefore, thermal management becomes an additional design consideration for robots intended to operate in hot outdoor environments. General-purpose quadruped platforms can provide conventional visual and ranging capabilities, but additional specialized sensors are required when the inspection task involves chemical analysis, concealed materials, or non-metallic substances.

Tracked and wheeled robotic platforms are also used for explosive ordnance disposal and related inspection tasks [22]. Their configuration can provide advantages in payload capacity and equipment integration, while mobility requirements may differ from those of compact quadruped platforms in environments containing narrow passages, steps, rails, and uneven railway ballast. From a sensing perspective, platforms that rely mainly on RGB cameras or metal-detection coils provide information from a narrower set of sensing modalities. Such configurations may not be sufficient for inspection tasks involving chemical-vapor analysis, concealed materials, or liquid contents inside opaque containers. The specialized sensing methods considered in this work address these

requirements through complementary detection modalities [4]-[11].

Communication reliability is another consideration for autonomous inspection robots. Wireless connectivity can become challenging in railway environments such as tunnels and other signal-obstructed areas. Loss of connectivity can interrupt remote monitoring and delay the transmission of robot data [23]. The reviewed systems address individual aspects of railway inspection, robotic mobility, sensing, or remote operation, while the requirements considered in this work involve combining these functions within a single mobile platform. In particular, the proposed design focuses on railway-specific environmental conditions such as thermal management and electromagnetic protection, together with multi-sensor threat inspection and communication backup. These combined requirements define the design gap addressed by the proposed platform.

5. LIST OF MODULES

The proposed robotic system is organized into five main modules. Each module is responsible for a specific part of sensing, movement, processing, protection and communication.

- **Module 1- Threat Detection and Analysis Module:** This module combines different sensing techniques for examining possible threats in the railway environment. Spatially Offset Raman Spectroscopy (SORS) is used for non-contact analysis of liquid containers [4], [5], while Ion Mobility Spectrometry (IMS) uses micro-vacuum sampling to analyse chemical vapors [6], [7]. Terahertz (THz) imaging is included for concealed-material inspection [8], [9], Ground Penetrating Radar (GPR) is used for railway ballast evaluation [10], and Mu-Metal-shielded Pulse Induction Metal Detection (PIMD) is used for detecting metallic objects [11].

- **Module 2- Navigation and Locomotion Module:** This module combines 3D solid-state Time-of-Flight (ToF) LiDAR, 60–77 GHz 3D/4D mmWave RADAR, RGB and thermal LWIR imaging, and a 9-axis MEMS IMU for navigation and environmental perception. The collected sensor information is used for simultaneous localization and mapping (SLAM) and for maintaining balance while the robot moves across steel rails and railway ballast.

- **Module 3- Processing and Control Module:** This module separates high-level processing from low-level control. The NVIDIA Jetson Orin Nano performs YOLOv8/v10 neural-network inference and point-cloud processing [3], [17], [18], while an STM32 microcontroller handles the real-time control functions. Communication between the two processing units is provided through an isolated CAN-Bus/UART interface, and the STM32 runs the kinematic and balance-control routines using bare-metal C++ with a target control frequency of 500 Hz.

- **Module 4- Thermal and EMI Protection Module:** This module provides thermal and electromagnetic protection for the robot's internal electronics. An IP65-rated 6061-T6 aluminium sub-chassis is used as the main protected enclosure and also provides electromagnetic shielding. A CNC-machined copper heat-pipe cooling arrangement is included for transferring heat away from the computing hardware, while nanoporous Aerogel insulation is provided around the battery compartment to reduce heat transfer.

- **Module 5: Communication and Safety Module:** This module manages the robot's communication and emergency protection functions. The system uses 4G LTE for normal communication and provides an 868/915 MHz LoRa link as a backup when cellular connectivity is unavailable [20]. A 1 TB NVMe SSD is used for local storage of sensor and mission data during offline operation. An optocoupled solid-state relay is included in the emergency interlock to isolate the motor power bus when an emergency-stop condition occurs.

6. SYSTEM DESIGN AND ARCHITECTURE

The proposed dual-mode quadruped robot is designed for security inspection in railway environments. The system combines multiple sensing methods with autonomous movement and is supported by separate hardware and software functions. The system design is organized into five main areas: high-level perception, low-level motion control, threat sensing, thermal and electromagnetic protection, and power and communication management.

6.1. System Architecture

The system uses a two-level computing architecture in which the high-level processor handles computationally intensive sensing tasks and the microcontroller manages real-time control functions. The two units communicate through isolated interfaces.

- **High-Level Processing Unit:** An NVIDIA Jetson Orin Nano with 8 GB memory is used for high-level processing [3]. It supports YOLOv8/v10 inference using CUDA and TensorRT [3], [17]-[19], processes 3D ToF LiDAR point-cloud data, and handles mmWave radar measurements. ROS 2 is used to manage the software components and support localization and mapping using sensor data [15].

- **Low-Level Control Unit:** An STM32 32-bit ARM Cortex microcontroller running bare-metal C++ is used for low-level motion control. It receives orientation information from the 9-axis IMU and performs the required kinematic calculations for controlling the joint and wheel actuators through PWM signals. Shielded twisted-pair cables are used for signal connections, with the cable shielding grounded at the aluminium compute enclosure to reduce electromagnetic interference.

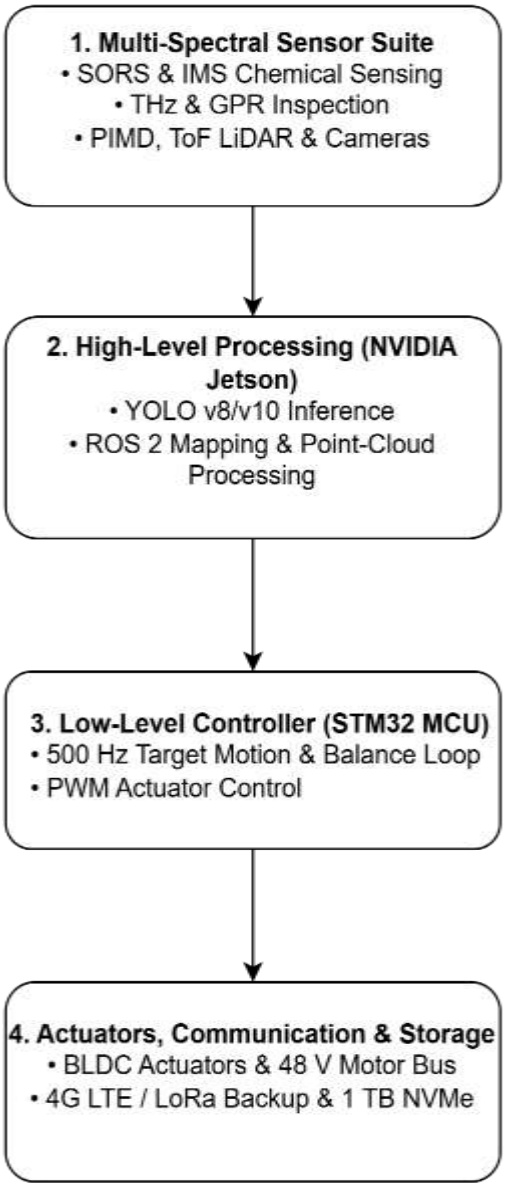


Fig-1: System Architecture

6.2 Hardware Placement and Enclosure Layout

The physical layout of the robot is divided into four main zones to separate the sensing, computing, battery and undercarriage components. This arrangement is intended to reduce interference between high-power components and sensitive electronic sensors.

1. **Front Sensor Assembly (PA12-GF Glass-Filled Nylon):** This section comprises the SORS unit with its 785 nm laser and sapphire window, IMS chemical-sampling unit with a micro-vacuum pump and PTFE filter, THz sensor, LWIR and 4K camera system and the front PIMD sensing coil.

2. **Main Body Core Sub-Chassis (1.5 mm IP65-rated 6061-T6 Aluminium):** The main body contains the Jetson Orin Nano, STM32 microcontroller, 1 TB NVMe SSD, 9-axis IMU, and voltage-conversion circuits. The aluminium enclosure also provides structural support and electromagnetic shielding for the internal electronics.

3. **Battery Safety Compartment:** The 48 V LiFePO4 battery pack is placed in a separate compartment. Nanoporous Aerogel insulation is provided around the battery enclosure to reduce heat transfer from the external environment.

4. **Belly and Undercarriage Array:** The lower section of the robot carries the ground-coupled GPR antennas, the PIMD coil with Mu-Metal shielding, the 3D ToF LiDAR, and the Doppler mmWave radar. These sensors are positioned below the main body to support ground and surrounding-environment inspection.

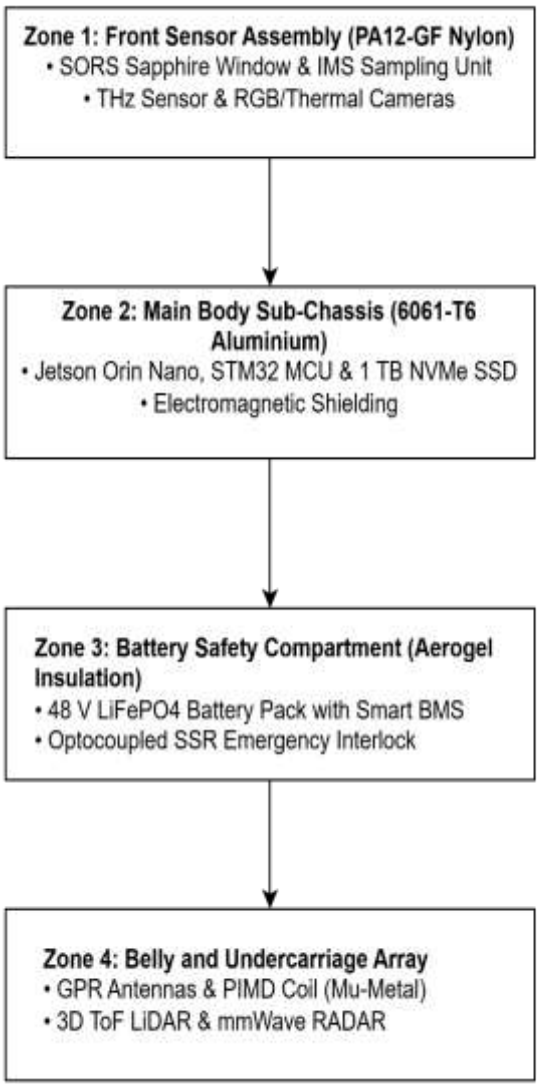


Fig-2: Hardware Placement Layout

6.3 Power Distribution and Emergency Stop System

The power system converts the 48 V output of the LiFePO4 battery pack into regulated 12 V and 5 V supply rails for the different electronic subsystems. A 100 V low-ESR capacitor bank is connected across the main power bus to reduce voltage disturbances caused by motor back-EMF.

The emergency-stop system provides an independent safety path for disconnecting the motor power supply. A physical E-STOP command or loss of the defined communication heartbeat causes the optocoupled Solid-State Relay (SSR) to isolate the

48 V motor bus. The Jetson Orin Nano and STM32 can remain powered through the regulated supply rails so that important diagnostic information can be stored on the 1 TB NVMe SSD.

(i) Power Distribution Flow Diagram

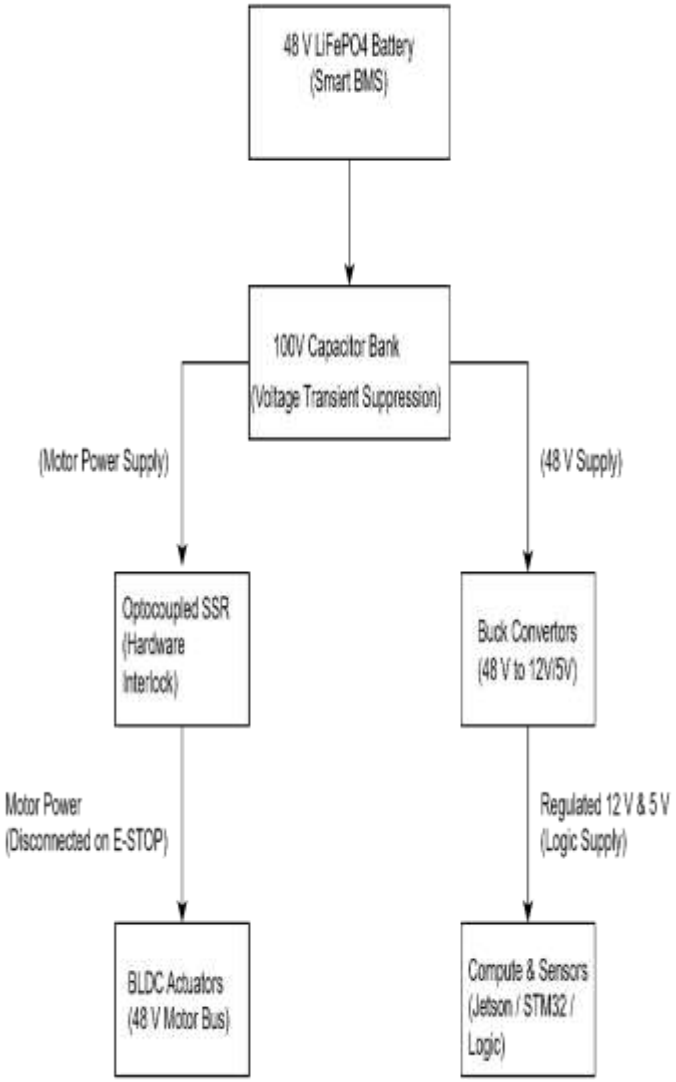


Fig-3: Power Distribution Flow

(ii) Emergency-Stop Sequence Diagram

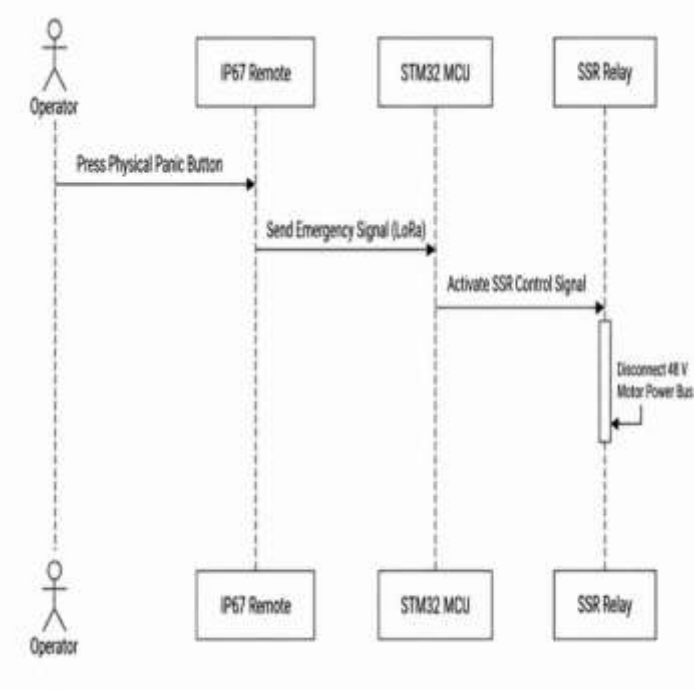


Fig-4: Emergency-Stop Workflow

6.4 System Use Case Diagram

The use case diagram shows the main interactions between the RPF field operator, the railway control system, the autonomous navigation functions, and the robot's low-level safety system.

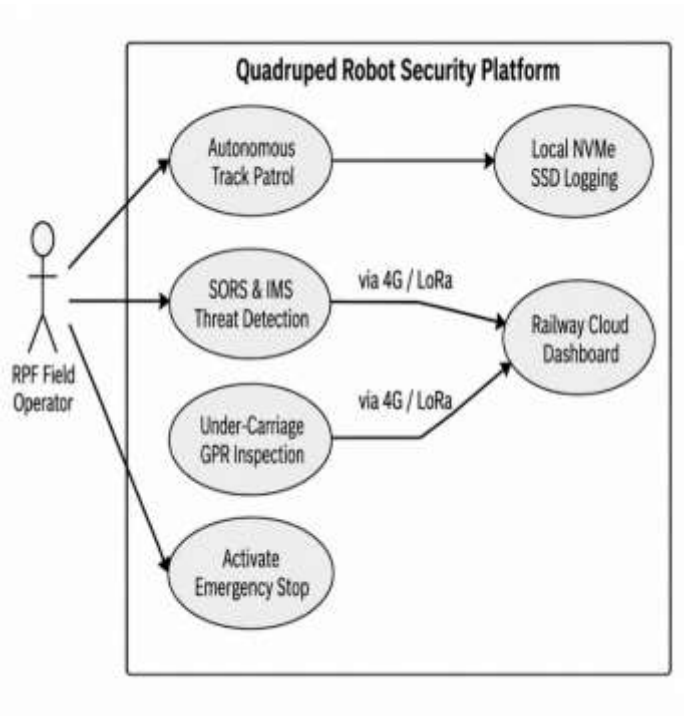


Fig-5: System Use Case Diagram

6.5 System Class Diagram

The class diagram represents the main software components used to organize the robot's perception, control, sensing, and data-logging functions. The architecture separates high-level processing from the low-level control tasks. The RobotController acts as the main control component of the

software system. It manages system states, monitors battery information, and handles emergency-stop commands. It is connected to the major processing and sensing components of the robot.

1. AIInferenceEngine: This component manages neural-network inference on the NVIDIA Jetson Orin Nano [3]. It also handles ROS 2-based localization and processing of spatial sensor data such as point clouds [15].

2. KinematicEngine: This component runs on the STM32 microcontroller and uses orientation information from the MEMS IMU to perform the required kinematic calculations. It generates PWM commands for the robot actuators.

3. ThreatSensorSuite: This component contains the software interfaces for the different threat-detection sensors, including SORS, IMS, THz imaging, GPR, and PIMD.

When a sensor or perception module detects an event that satisfies the defined alert conditions, a ThreatEvent record can be created. This record may contain the detected event, confidence information, location data, and timestamp. The information is then passed to the DatabaseLogger, which stores the event data on the onboard 1 TB NVMe SSD.

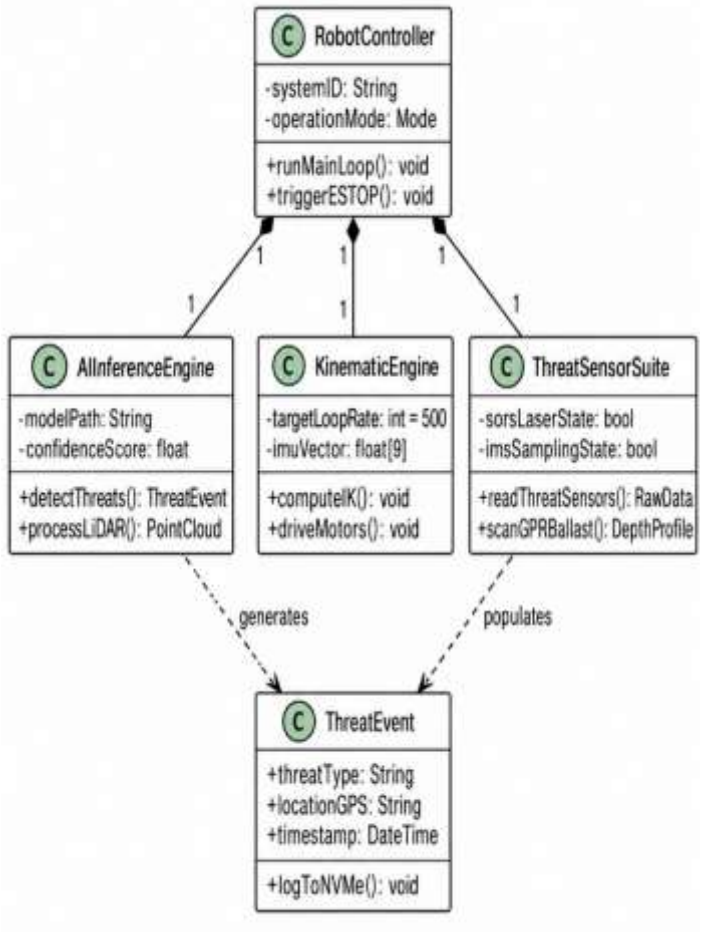


Fig-6: System Class Diagram

6.6 Thermal Management State Machine Diagram

The thermal management system is designed to reduce heat buildup around the onboard computing hardware during operation in hot railway environments. A copper heat-pipe arrangement connected to external radiator fins is used to transfer heat away from the processor enclosure. Aerogel insulation is provided around the battery compartment to reduce heat transfer. The state machine monitors the thermal condition of the system and allows the robot to respond when the temperature increases beyond the defined operating range.

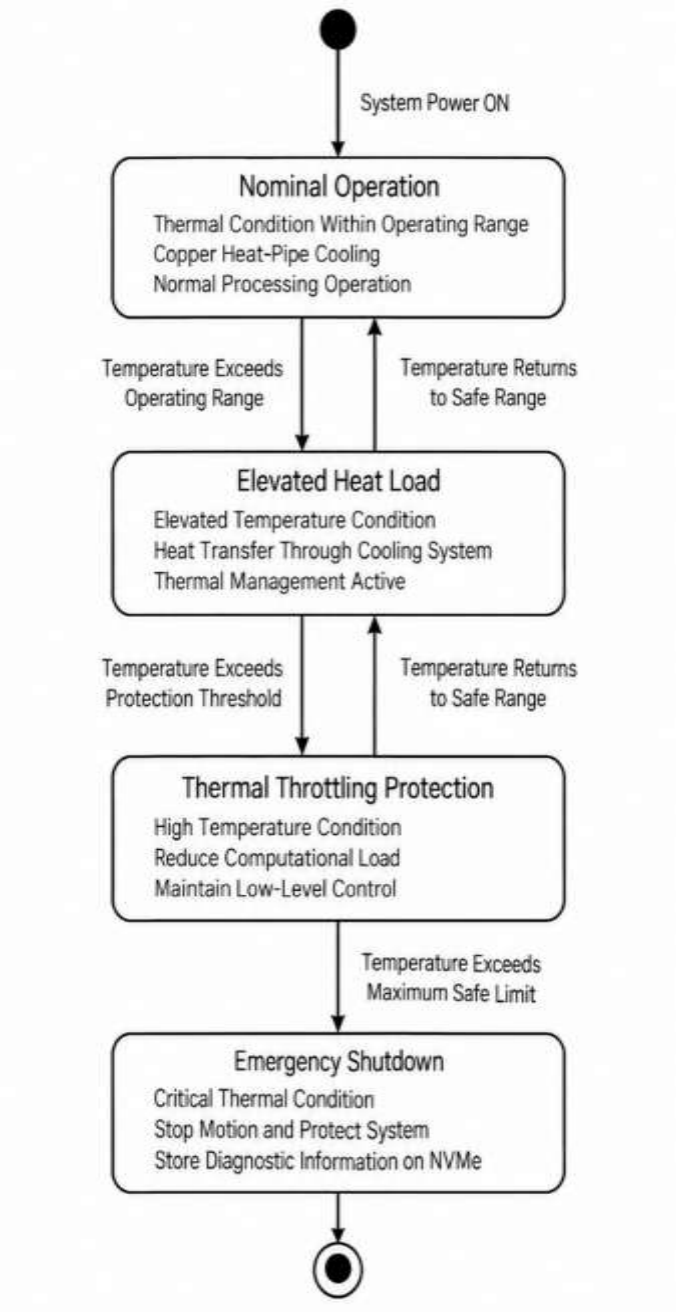


Fig-7: Thermal Management Flow

Note: The thermal thresholds, computational-load reduction levels, and emergency shutdown conditions are design parameters to be determined through experimental thermal characterization of the completed prototype. The state machine represents the intended thermal-management logic rather than measured operating thresholds.

6.7 Communication and Failover Sequence Diagram

The communication system uses 4G LTE as the primary connection for transmitting robot data. If the cellular connection becomes unavailable, the system can switch to the 868/915 MHz LoRa link for important alerts and telemetry [20]. Sensor data that cannot be transmitted immediately is stored locally on the 1 TB NVMe SSD. Once the primary connection is restored, the stored data can be synchronized with the remote monitoring system.

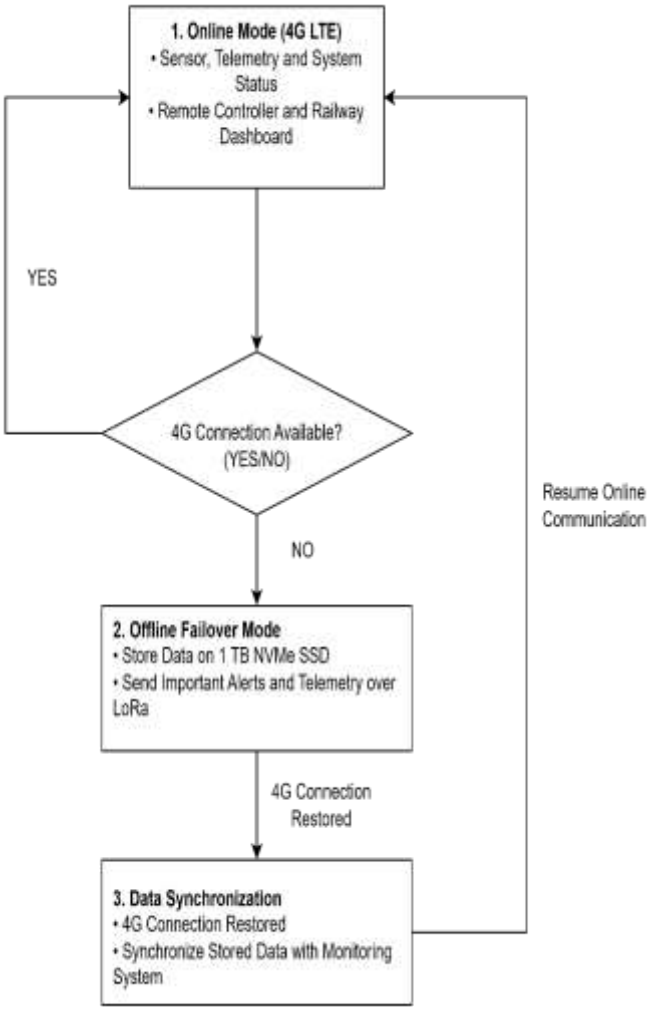


Fig-8: Communication and Failover Flow Diagram

7. SYSTEM OVERVIEW

Problem Statement and System Objectives

Railway security inspections require methods for identifying concealed hazardous materials and suspected narcotic substances across different inspection areas. Existing screening activities commonly involve fixed inspection equipment and manual checks, which provide limited mobility inside railway coaches, along platforms, and across railway yards. A mobile robotic platform could support security personnel by carrying sensing equipment into areas that may be difficult or potentially unsafe to inspect directly, while enabling more flexible coverage of inspection areas.

The main objective of the proposed system is to develop an indigenous quadruped robotic platform for railway security inspection. The robot is intended to provide mobile sensing, support autonomous or remotely supervised movement, inspect selected areas around the railway track bed, and record relevant sensor events together with location and time information for subsequent analysis.

Advantages and Limitations of the Proposed System

Advantages

- **Non-Contact Multi-Modal Screening:** The proposed sensing system combines non-contact and vapor-based inspection methods for different threat types. SORS is intended for non-contact analysis of liquid containers [4], [5], while IMS is used for chemical-vapor analysis [6], [7].
- **Environmental Protection:** The robot includes an aluminium sub-chassis, thermal-management components, and electromagnetic shielding to protect the internal electronics during outdoor railway operation. The design also considers the effects of elevated temperatures and electromagnetic interference on the onboard hardware.
- **Offline Operation and Communication Backup:** The system provides a LoRa communication link as a backup when the primary cellular connection becomes unavailable [20]. Important alerts and telemetry can be transmitted to the remote controller using the backup link, while sensor and event data that cannot be transmitted immediately are stored locally on the 1 TB NVMe SSD. When the primary connection is restored, the stored data can be synchronized with the monitoring system.
- **Real-Time Motion Control:** The STM32-based low-level controller uses bare-metal C++ for motion and balance calculations. The control architecture is designed around a target control frequency of 500 Hz to support responsive motion and balance control over uneven railway surfaces.

Limitations

- **Initial Prototype Cost:** The inclusion of specialized sensors such as THz, SORS, and GPR is expected to increase the prototype cost compared with a quadruped platform equipped only with conventional cameras and basic ranging sensors.
- **Maintenance and Calibration:** The specialized sensing components require regular maintenance and calibration to maintain reliable measurements. Dust, contamination, and repeated outdoor operation may affect optical and chemical-sensing components, particularly during extended deployment in railway environments.

8. SYSTEM ANALYSIS

The proposed system is analysed using performance parameters related to safety, real-time control, AI processing, and local data storage.

Performance Parameter	Value/ Design Target	Technical Description
Emergency Stop Response Target	< 2.0 ms*	Target response time of the emergency-stop mechanism using an optocoupled SSR to isolate the motor power bus.
Real-Time Kinematic Motion Control	500 Hz*	Target control frequency for the low-level balance and motion-control loop, corresponding to a 2 ms control cycle.
YOLO v8/v10 Inference Throughput	35–42 FPS*	Target inference range for the proposed YOLO-based perception pipeline using TensorRT and FP16 acceleration on the Jetson Orin Nano [3], [17]-[19].
Local Data Logging Throughput	Up to 3,500 MB/s*	Storage-device specification associated with the selected PCIe Gen4 NVMe SSD under suitable sequential-write conditions.

Note: The values presented in this table represent a combination of design targets, component specifications, and intended performance values. The 500 Hz control-loop frequency and YOLO inference rate are target values to be validated experimentally. The NVMe throughput represents the storage-device specification and does not indicate the actual robot data-logging throughput. The emergency-stop response time is a target value subject to hardware-level validation.

1. **Response Time and Interlock Latency:** The low-level controller is designed to execute the motion-control loop at a defined rate suitable for real-time balance control. The emergency interlock monitors the operator command and the communication heartbeat. If an emergency-stop command is received or the defined communication heartbeat is lost, the optocoupled solid-state relay disconnects the 48 V motor power bus while keeping the logic supply active for system-status recording.

2. **CPU/GPU Compute Optimization:** YOLOv8/v10 models can be optimized using TensorRT with FP16 acceleration on the Jetson Orin Nano [3], [17]-[19]. This approach is intended to improve inference efficiency while keeping the computational workload within the available processing and power limits of the platform.

3. **Memory and NVMe Storage:** The local storage system is intended to record point-cloud, thermal, spectral, and other telemetry data on the 1 TB PCIe Gen4 M.2 NVMe SSD. The available storage bandwidth depends on the selected SSD and the actual data-recording configuration. Local storage allows sensor information to be retained when network connectivity is unavailable and synchronized with the remote system after connectivity is restored.

9. CONCLUSION

This paper presented the proposed design and system architecture of an indigenous dual-mode quadruped robot intended for security inspection in railway environments. The platform combines multiple sensing technologies, including SORS, IMS, THz, GPR, and PIMD, with a 6061-T6 aluminium structural enclosure for protecting the internal electronics. The proposed architecture brings sensing, mobility, computing, thermal management, communication, and safety functions together within a single robotic platform.

The two-level computing architecture separates high-level perception from low-level motion control. The Jetson Orin Nano is intended to handle computationally intensive perception and sensing tasks, while the STM32 controller manages low-level motion and balance functions. A control frequency of 500 Hz is defined as a design target for the low-level control loop. The thermal-management design incorporates copper heat pipes and Aerogel insulation to support heat management around the computing and battery sections. These measures are intended to improve heat transfer from the electronics and reduce external heat transfer to the battery compartment during operation in hot outdoor railway environments.

For communication and safety, the proposed platform uses 4G LTE as the primary communication link, with LoRa available as a backup when cellular connectivity is unavailable. A 1 TB NVMe SSD provides local storage for sensor and system data during periods of limited connectivity, while the hardware emergency interlock is designed to disconnect the motor power supply during an emergency condition. Overall, the proposed system is intended to provide a mobile inspection platform that can assist security personnel by combining multi-modal sensing, quadruped mobility, onboard computing, local data

storage, and communication backup within a single architecture.

10. FUTURE ENHANCEMENTS

Future development of the proposed robotic platform can focus on improving multi-robot coordination, autonomous charging, and communication coverage. The following enhancements are considered for future versions of the system:

1. **Multi-Robot Coordination:** Future versions of the system could support communication and task coordination between multiple quadruped robots using ROS 2 [15]. This would allow multiple robots to coordinate their movements and divide inspection tasks across larger railway yards and stations.
2. **Autonomous Docking and Charging:** A future version could include an inductive charging interface mounted on the underside of the robot together with dedicated docking stations. When the battery level becomes low, the robot could return to a docking station and recharge without requiring manual battery replacement.
3. **Drone-Assisted Communication and Surveillance:** Future development could integrate the quadruped platform with a small aerial vehicle to extend communication coverage in areas where the ground robot has limited connectivity. The aerial platform could also provide an elevated camera view to support inspection of larger or difficult-to-access areas within railway areas.

11. REFERENCES

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