# DESIGN AND DEVELOPMENT OF AN AUTONOMOUS SPHERICAL ROBOT FOR INTELLIGENT POWER GRID INSPECTION AND FAULT DETECTION

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**Keywords:**

Autonomous Spherical Robot (ASR), Power grid inspection, Omnidirectional mobility, Barycentre offset mechanism, Thermal imaging, Autonomous navigation, Simultaneous Localization and Mapping (SLAM), Wireless control.

**Introduction:**

1. When we think of electrical substations, we picture a tangle of high-voltage equipment that is humming unobtrusively at the margins of urban life, and still, they play a very important role in keeping our cities running. In this world where we are increasingly dependent on electricity, these substations have become the lynchpin of modern power distribution. Reliable substation operation is now becoming vital for system stability and public safety as the demand for electricity surges due to urban expansion, transportation electrification, and digital infrastructures.
2. In traditional settings the inspections have mostly depended on human operators navigating dangerous zones, often in extreme weather or cramped spaces. There are limitations to this approach. It is slow, risky, and prone to human error. Despite the introduction of certain robotic systems, their mobility and adaptability are often compromised. For instance, the wheeled and tracked robots might not be able to survive in rough, obstacle-ridden conditions of substations.
3. To rectify these shortcomings, this project proposes the design and development of a spherical robot which is able to navigate substation environments and carry out intelligent inspection tasks. The spherical form factor is very beneficial as it enables omnidirectional motion, smooth rolling over uneven terrain, and complete sealing of internal electronics, which improves durability against environmental factors like dust, moisture, and electromagnetic interference. Thermal imaging and heat signature analysis can detect faults before they get out of hand. In particular, spherical robots offer a unique opportunity to carve out a niche in environments where agility and resilience are paramount.

Figure 1: Power Grid Infrastructure

**Objectives:**

This project focuses on creating, designing, and preliminarily implementing a spherical robot that can inspect electrical power distribution stations.

The scope of this project includes:

- To propose a complete software and hardware framework for a novel spherical robot to explore electrical power distribution stations, including tight and risky spaces.
- To use thermal vision system for finding electrical faults and problems like overheating, insulation failure, and signal disturbances.
- To cut down on manual inspection in high-voltage zones, thus boosting the safety and operational efficiency.

**Methodology:**

Each phase is executed in a sequence, starting with identifying the need for inspection, followed by studying and analysing the existing technologies, designing the spherical robot, fabricating the prototype, and finally validating its performance in substation environments.

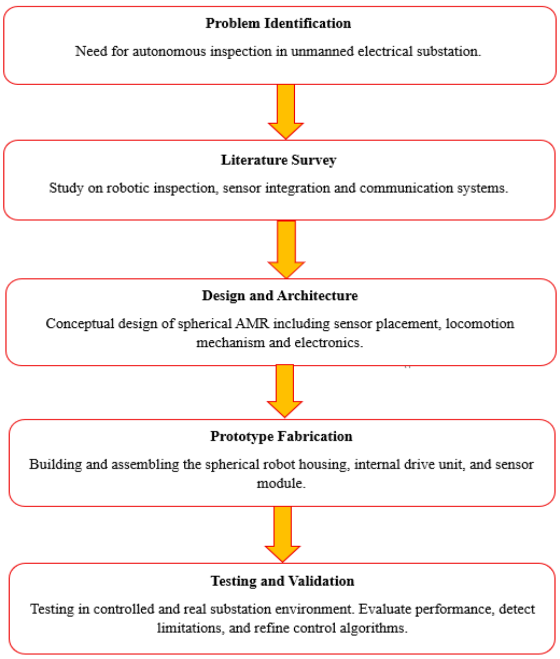


Figure 2: Methodology

This project offers a creative solution to a major problem and that is keeping the power grids safe and reliable. Instead of relying on costly drones or dicey manual checks, we have developed a compact and reliable robot. To overcome some of such challenges in the electrical substations we propose an Autonomous Spherical Robot that can navigate smoothly within power distribution stations, detect electrical faults, and transmit real-time data to operators. Equipped with thermal imaging and visual camera, IMU sensor, and an AI-driven fault analysis system, the robot should be able to autonomously navigates substations and detect overheating components, insulation failures, and electrical anomalies. At the heart of the control system of this robot lies a pendulum-driven actuation segment mounted inside the spherical shell. The pendulum or mass attached at the bottom helps to define the Center of Gravity (CoG) correctly. The propulsion method involves shifting the internal Center of Mass (CoM) by sliding the pendulum at the bottom. The pendulum is coupled to two DC motors and two servo motors. The DC motors control the forward and backward rolling by rotating the wheels attached to the shell along the sagittal plane. The servo motors adjust the pendulum's tilt or orientation to allow better balance and turning dynamics. Arduino Nano board acts as a primary microcontroller which controls the movement of the motors using a Bluetooth module. IMU sensor is used for stability. The Raspberry Pi 4 single-board computer is used as a second microcontroller which handles the thermal image processing and analysis and also creates a 2D map of the substation environment. The project adopts a structured, multi-phase methodology which includes problem identification, literature survey, design and architecture, prototype fabrication, and testing and validation. Thus, the project systematically achieves the objectives within defined constraints.

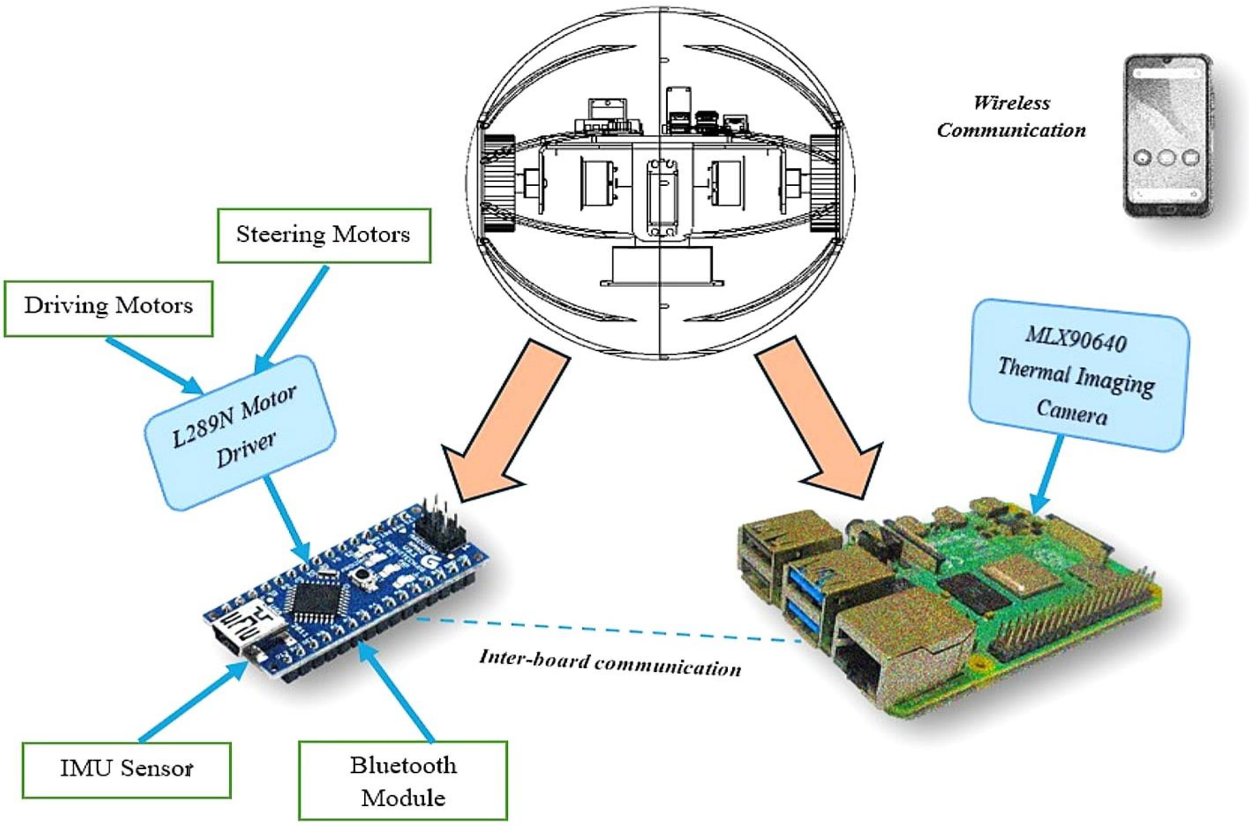


Figure 3: Architecture of the model

**Result and Conclusion:**

The final model of the project was successfully developed and assembled, as shown in figure 4 below. All major components such as the Arduino Nano, Raspberry Pi 4, MPU6050, thermal camera, L298N motor driver, servo motors, DC motors, and Bluetooth control module, were mounted on to the main chassis. The internal assembly was completed with proper electronic wiring, incorporating a common ground across all modules to ensure reliable operation. Electromagnetic shielding was integrated to protect sensitive components from external interference, ensuring smooth and dependable system performance. During testing the model had a smooth and stable movement, precise control response, and reliable wireless operation. The internal assembly provided proper balance and ensured protection for all electronic parts. The system effectively performed real-time motion control through Bluetooth commands with very less delay and high accuracy. Overall, the fabricated prototype achieved the desired objectives of efficient control, stable communication, and safe operation, thereby validating the design, integration, and performance of the complete system.

Figure 4: The Final Prototype

The thermal images captured by the thermal camera illustrate temperature variations across a power grid component. The color changes in the images represent differences in surface temperature warmer areas appear in yellow or orange, while cooler regions are shown in darker shades such as purple or black. This variation occurs because the thermal camera detects infrared radiation emitted by objects, which increases with temperature. In a power grid system, such temperature differences can indicate potential faults or abnormal heating due to overloading, loose connections, or insulation failure. By analyzing these color patterns, hot spots can be easily identified, allowing for early detection of faults before they lead to severe damage or power failure. The transition from lighter to darker colors clearly shows the heat distribution, helping to assess the efficiency and safety of electrical components. Thus, the thermal camera provides a non-contact, real-time monitoring solution for effective fault detection and maintenance in power grids.

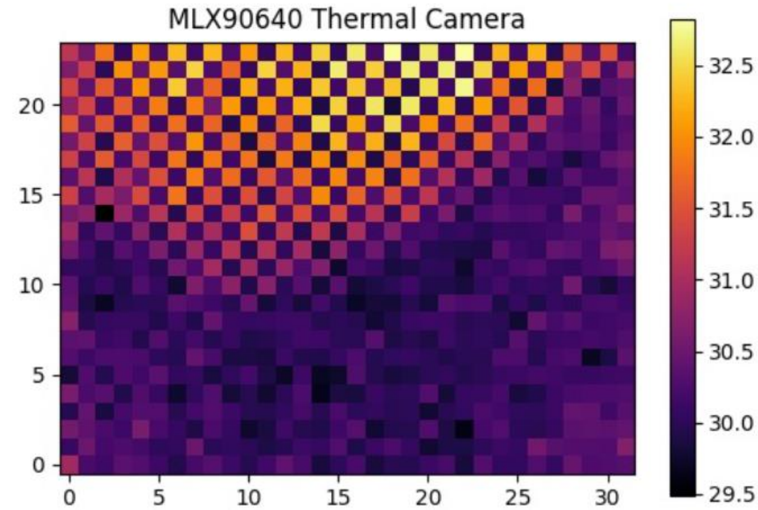

Figure 5: Thermal Image Visualization

In this project, ORB-SLAM3 was employed to generate a spatial map of the inspection environment using a monocular camera. The SLAM pipeline successfully produced a dense and consistent 3D feature-based map as shown in the experimental output in figure 6. The map visually highlights multiple connected indoor corridors and pathways, with loop closures correctly identified when the camera revisited previously explored regions. This demonstrates that the SLAM system was able to maintain global consistency and mitigate drift over long trajectories an essential requirement for autonomous inspection tasks in power grid infrastructures. The generated map consists of keyframes and sparse feature points, which collectively represent the geometric layout of the environment. The ORB-SLAM3 continuously estimates the pose that is the position and orientation of the camera with respect to the map frame. This real-time pose information is the primary input required for autonomous navigation.

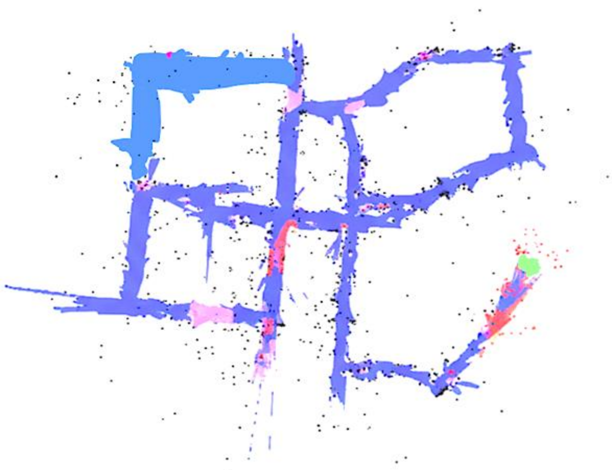
Figure 6: SLAM Map

This project successfully established the conceptual framework for a spherical robot designed for inspection and fault detection in electrical power grids. The objective of this project was to build a smart spherical robot equipped with a thermal camera to effectively detect faults in power grid. It mixed mechanical stability, wireless control, and intelligent monitoring in a compact and solid profile. The project has proved that robotic mobility and thermal visualization could jointly develop a useful, simple and low budget solution for fault detection without the need for direct contact. This technology helps maintain electrical infrastructure more safely and efficiently, reducing the occurrence of power outages and improving operational reliability.

**Project Outcome and Industry Relevance:**
The practical implementation of this project can lead to:

- Improved safety by reducing human exposure to dangerous environments
- Cost reduction in maintenance and inspection operations
- Increased efficiency and accuracy through automated data collection
- Scalability for deployment in large industrial systems

Furthermore, the compact spherical design allows for easy deployment, durability, and adaptability, making it suitable for real-world industrial applications.
This research advances the field of mobile robotics by evaluating the efficacy of spherical locomotion as a robust alternative to conventional wheeled or tracked configurations. By leveraging a design characterized by a naturally low center of gravity and a sealed external shell, the proposed system achieves a unique balance of inherent stability and mechanical resilience. The reduction in external moving parts not only mitigates the risk of mechanical failure in ingress-heavy environments but also facilitates omnidirectional manoeuvrability, which is essential for navigating the spatial constraints of hazardous or high-consequence settings. Moreover, this work extends the current discourse on autonomous inspection frameworks by integrating sophisticated sensor fusion techniques and real-time decision-making protocols, thereby enhancing the reliability of robotic agents in infrastructure monitoring.
The practical utility of this system is particularly evident in sectors where human intervention is limited by safety risks or structural complexity. Beyond its primary application in power transmission and utility management, the robot's adaptable architecture offers significant promise for the oil, gas, and mining industries, where environmental adaptability is essential. Additionally, the system provides a scalable solution for civil engineering inspections, defence-oriented surveillance, and the evolving needs of smart city infrastructure. By addressing the fundamental challenges of navigation and control within a spherical form factor, this project contributes a versatile platform to the next generation of autonomous industrial automation, bridging the gap between theoretical robotic design and high-stakes operational requirements.

**Working Model vs. Simulation/Study:**
We developed a fully functional physical prototype for this project rather than being limited to simulation or study. In addition to the hardware implementation, supporting simulations using tools such as SolidWorks were conducted to optimize the design and ensure structural and functional reliability prior to fabrication.

**Project Outcomes and Learnings:**
The autonomous spherical robot is designed to perform inspection and monitoring tasks in challenging and confined environments with minimal human intervention. The project demonstrated the integration of mechanical design, sensor systems, and intelligent control algorithms into a compact, robust robotic platform.
The outcomes of this project include:

- Development of a stable and omnidirectional locomotion system using a spherical structure.
- Implementation of autonomous navigation and thus enabling the robot to operate in unstructured environments.
- Integration of sensing technologies such as thermal camera and sensors for real-time data acquisition.
- Simulation and validation of robot performance using tools like SolidWorks to assure structural integrity and functional feasibility.

Overall, the project results in a versatile inspection robot prototype capable of operating where conventional wheeled or legged robots may face limitations.

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**Future Scope:**

The future scope of this project includes:

1. We would like to focus on implementing advanced algorithms such as RRT* so that the robot can continuously optimize its path length. Upgrading the path planning can help the robot to work better in complex and unstructured environments.
2. Another area for improvement is the integration of advanced image processing and machine learning technologies which would allow better analysis of the thermal data we obtain. By training AI models on large sets of thermal images, the machines would be able to automatically detect faults, classify their severity, and make predictions about future fault conditions as they begin to occur. Thus, the machine will be a proactive diagnostic instrument rather than a simple means of website fault detection.
3. Further optimization of the internal drive mechanism can enhance speed and energy efficiency, stability on uneven or inclined surfaces, and the ability to traverse more complex terrains.