AUTONOMOUS MICRO-DRONE SYSTEM FOR REAL-TIME POWER LINE INSPECTION, MICRO-CRACK DETECTION AND ON-SPOT CONDUCTIVE REPAIR

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ABSTRACT

An autonomous micro-drone system for power line health management is presented, integrating micro-robotics, multi-modal sensing, edge artificial intelligence, precision conductive repair, and secure wireless communication. The system autonomously traverses energized electrical conductors using passive magnetic adhesion and active micro-clamps, enabling real-time detection of micro-cracks and localized defects at micrometer-scale resolution. Upon defect confirmation, the drone performs on-spot conductive micro-repair by injecting a specially formulated conductive restoration gel, followed by rapid in-situ curing and post-repair electrical and mechanical verification. All inspection and repair data are cryptographically signed and transmitted to utility cloud systems for compliance, analytics, and predictive maintenance. The invention eliminates the need for line shutdowns, significantly reduces maintenance cost, improves grid reliability, and enables scalable autonomous inspection across transmission and distribution networks.

1. FIELD OF THE INVENTION

The present invention relates to **electrical infrastructure maintenance**, specifically to **power transmission and distribution systems**. It integrates technologies from **robotics, artificial intelligence, sensor systems, materials science, and wireless communication**. More particularly, the invention describes an **autonomous micro-robotic system** capable of safely traversing energized power conductors, performing high-precision non-destructive inspection, autonomously detecting micro-scale defects, executing in-situ conductive repairs, and securely reporting verified maintenance records without interrupting power delivery.

2. BACKGROUND OF THE INVENTION

2.1 Power Line Degradation Challenges

Electrical transmission and distribution lines operate continuously under harsh environmental conditions, including thermal cycling, wind-induced vibration, moisture ingress, ultraviolet exposure, corrosion, and mechanical fatigue. Over long operational lifetimes, these stresses lead to micro-cracks, corrosion pits, insulation degradation, strand fatigue, and increased electrical resistance.

2.2 Limitations of Existing Inspection Methods

- **Manual inspection** is hazardous, labor-intensive, weather-dependent, and infrequent.
- **Tethered robotic systems** have limited autonomy and operational range.
- **Aerial drones** lack physical contact, cannot perform micro-repairs, and are constrained by electromagnetic interference near high-voltage lines.

2.3 Consequences of Undetected Defects

Undetected micro-defects propagate over time, leading to conductor overheating, strand failure, unplanned outages, revenue loss, and large-scale reconductoring costs.

2.4 Need for the Invention

There exists no existing solution capable of **autonomous energized inspection and micro-repair** with verified documentation. This invention addresses this gap through a fully integrated autonomous system.

3. OBJECTIVES OF THE INVENTION

The primary objectives include:

- Safe autonomous traversal of energized conductors
- Micrometer-scale defect detection using multi-modal sensing
- Precision in-situ conductive repair
- Rapid curing and post-repair verification

- Secure long-range data transmission
- Scalable fleet-based operation
- Regulatory compliance and auditability

4. SUMMARY OF THE INVENTION

The invention provides a **fingertip-to-palm sized autonomous micro-drone** that adheres to energized conductors using passive magnetic wheels and active micro-clamps. The drone continuously scans conductors using eddy-current, optical, thermal, and ultrasonic sensors. An onboard AI model classifies defects and determines repair eligibility. Repairable defects are autonomously injected with conductive gel, cured using UV/thermal energy, verified for electrical and mechanical integrity, and securely reported to utility cloud systems.

5. DETAILED DESCRIPTION OF THE INVENTION

5.1 Hardware Architecture

- **Locomotion Module:** Magnetic wheels + servo-controlled micro-clamps
- **Chassis:** Aluminum alloy with Faraday shielding and environmental sealing
- **Sensor Suite:** Eddy-current, optical macro camera, thermal imaging, ultrasonic probe
- **Repair Module:** Micro-piston injection pump with conductive gel
- **Curing Unit:** UV and thermal hybrid curing
- **Verification Module:** Conductivity and adhesion testing
- **Power System:** Li-polymer battery with optional energy harvesting
- **Communication:** LoRaWAN, 5G, mesh, satellite (encrypted)

5.2 Software Architecture

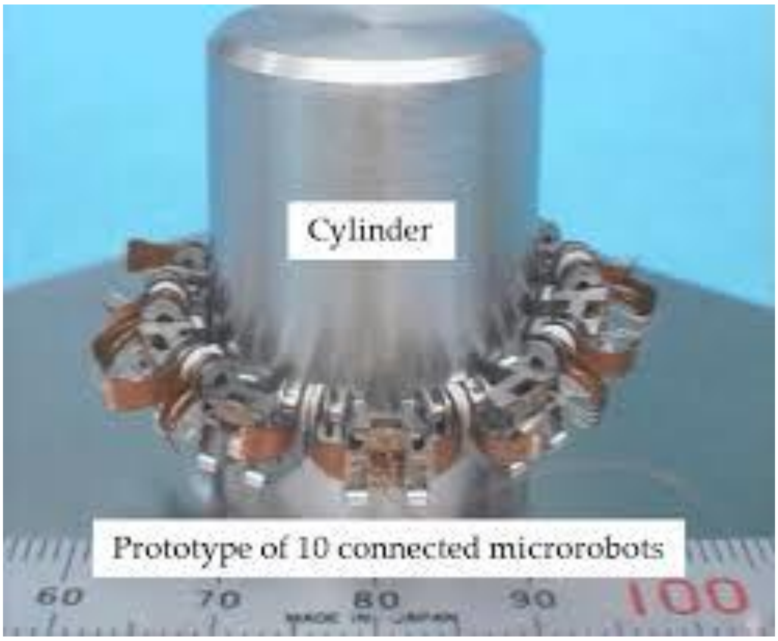
- Sensor fusion and signal preprocessing
- Edge AI defect detection and classification
- Autonomous repair decision logic
- Secure logging and cryptographic signing
- Fleet orchestration and cloud integration

5.3 Operational Workflow

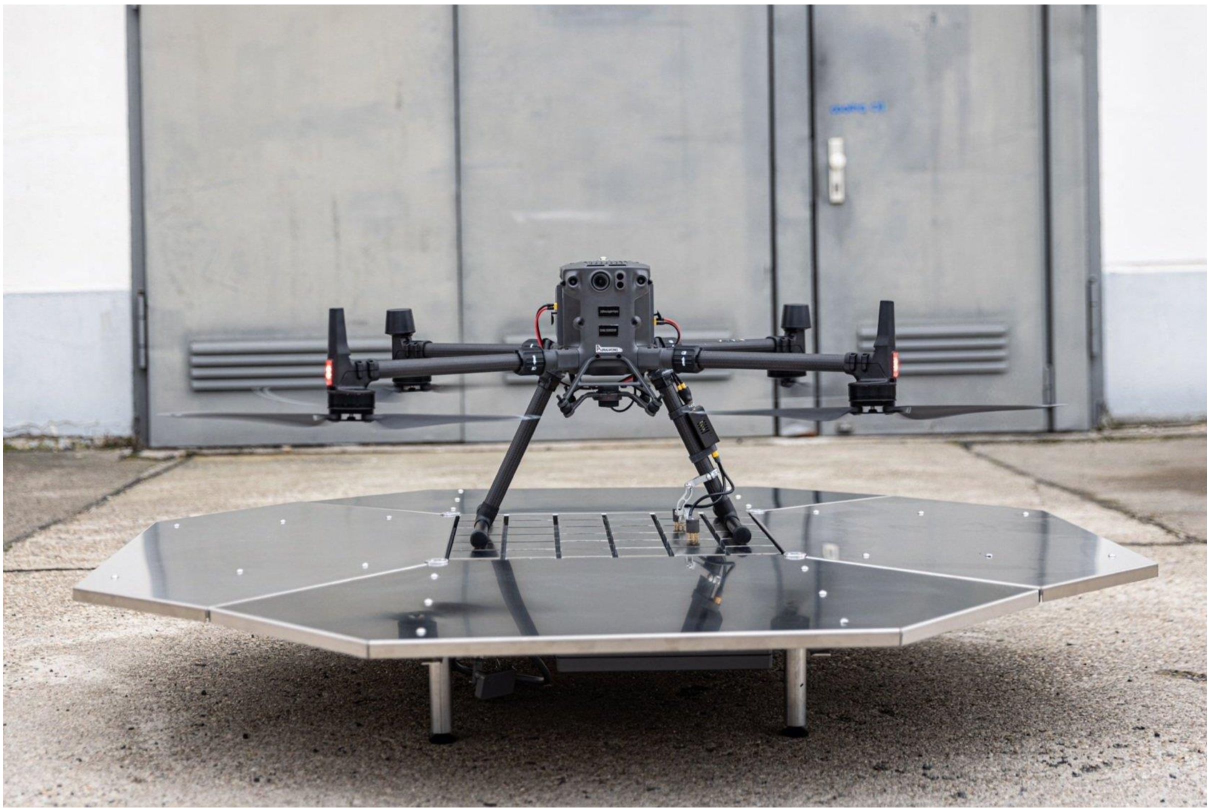
Deployment → Inspection → Defect Detection → Repair → Verification → Data Transmission → Return or Continue Mission

6. DRAWINGS AND FIGURES

System Architecture & Hardware Layout



Base Station & Repair Process



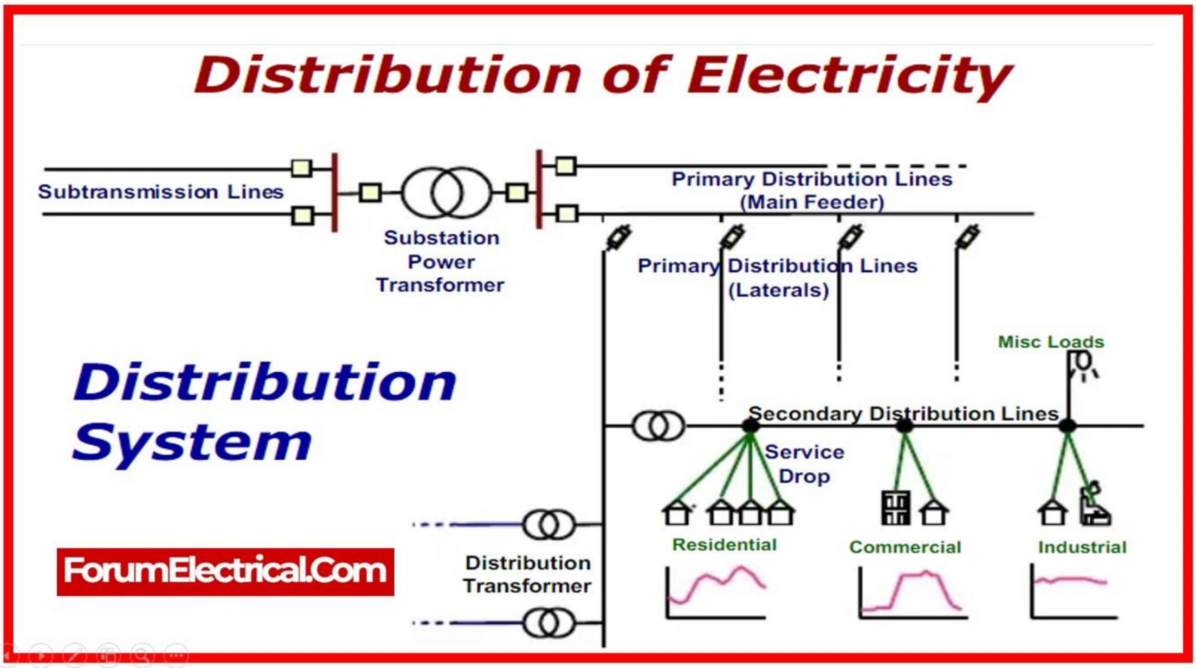


Figure Descriptions:

- **Figure 1:** Micro-drone positioned on energized conductor
- **Figure 2:** Sensor suite arrangement
- **Figure 3:** Micro-injection and curing system
- **Figure 4:** Pole-mounted autonomous base station
- **Figure 5:** End-to-end repair timeline

7. ADVANTAGES OF THE INVENTION

- No power shutdown required
- 60–80% reduction in maintenance costs
- Eliminates human exposure to high voltage
- Enables frequent inspections
- Predictive maintenance capability
- Cryptographically verifiable repair records
- Scalable to thousands of kilometers

8. APPLICATIONS OF THE INVENTION

Primary Applications

- High-voltage transmission lines
- Distribution networks
- Industrial busbars and data centers
- Renewable energy interconnects

Secondary Applications

- Railway electrification systems
- Offshore and underground cables
- Telecommunications infrastructure

9. FUTURE ENHANCEMENTS

- Multi-drone swarm coordination
- Adaptive and self-healing gel chemistry
- Fully autonomous base stations
- Predictive AI-driven maintenance planning
- Enhanced electromagnetic energy harvesting

10. CLAIMS

Claim 1. An autonomous micro-drone system for inspection and on-spot repair of energized power conductors, comprising:
- a locomotion module with passive magnetic wheels and servo-based micro-clamps for stable traversal and positioning on the conductor;
- a multi-modal sensor suite including at least an eddy-current probe, an optical camera, a thermal camera, and an ultrasonic sensor for micro-defect detection;
- an edge-compute module executing an AI model to classify defect type and determine repair actions based on fused sensor data;
- a precision micro-injection module for dispensing a conductive restoration gel onto a

detected defect;
- a curing assembly using ultraviolet and/or thermal energy to cure the dispensed gel;
- a verification module to measure restored electrical conductivity and mechanical adhesion of the repair; and
- a secure communications module for transmitting encrypted and cryptographically-signed telemetry.

Claim 2. The system of claim 1, wherein the locomotion module includes dual neodymium magnetic wheels generating 20–50 N adhesion force per wheel, a compliant suspension with ±5 mm travel, and servo-controlled micro-clamps for stabilization during repair operations.

Claim 3. The system of claim 1, wherein the edge-compute module includes a neural processing unit (NPU) and runs a convolutional neural network (CNN) for defect classification, and wherein the micro-injection module comprises a stepper-driven piston pump dispensing 0.1–10 µL doses of gel with a positioning accuracy of ≤100 µm.

Claim 4. The system of claim 1, wherein the conductive restoration gel comprises a rapid-cure epoxy matrix with a conductive filler of metallic or graphene nanoparticles, exhibiting a post-cure electrical conductivity of ≥100 S/m and an adhesion strength of ≥5 MPa.

Claim 5. The system of claim 1, further comprising a fleet orchestration system wherein a plurality of said micro-drones are managed from a cloud platform that assigns missions, coordinates with distributed base stations for automated inductive charging and gel refill, and aggregates signed repair data into an audit trail.

Claim 6. A method for autonomous micro-repair of energized power conductors using the system of claim 1, the method comprising the steps of:
- autonomously traversing the conductor while performing multi-sensor scanning;
- detecting and classifying a micro-defect using the onboard AI model;
- aligning a nozzle of the micro-injection module with the defect;
- dispensing a metered dose of conductive restoration gel;
- curing the gel using ultraviolet and/or thermal energy;
- verifying the repair by measuring electrical conductivity and mechanical adhesion;

and

- recording, cryptographically signing, and transmitting repair telemetry.

Claim 7. The system of claim 1, wherein the verification module performs a DC resistance measurement, a vibration-based adhesion test, and a post-repair optical imaging check to confirm the success of the repair.

11. SUMMARY AND CONCLUSION

This invention introduces a **transformational approach** to power infrastructure maintenance by enabling **autonomous, energized, micro-scale inspection and repair**. By combining robotics, AI, sensing, and materials science, the system delivers unmatched safety, cost efficiency, scalability, and regulatory compliance. The invention empowers utilities to shift from reactive maintenance to predictive, data-driven asset management, ensuring long-term grid reliability and resilience.