

Autonomous Robot for Aerial Marker Ball Deployment and Retrieval on Power Transmission Lines

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Abstract:

Aircraft warning spheres are installed on overhead power transmission lines to improve conductor visibility for low-flying aircraft and helicopters, thereby reducing the risk of aerial collisions. Conventional installation and replacement operations are generally carried out using helicopters, cranes, or scheduled transmission-line outages, resulting in high operational costs, increased safety risks, and interruptions to power delivery. To address these limitations, this study presents the design, development, and experimental validation of a mobile robotic platform capable of autonomously installing and removing aircraft warning spheres while travelling directly on overhead transmission-line conductors. The proposed robot combines a compact conductor-traversing mechanism with a dedicated quick-release clamping device and a suspended capsule-shaped battery module that improves stability under inclined operating conditions and wind-induced disturbances. Mechanical analyses were conducted to determine the required characteristics of the clamping system, and numerical simulations were performed to evaluate the robot's mobility, stability, and mechanical performance. A full-scale prototype was fabricated and experimentally evaluated on a transmission-line test platform. The results demonstrated that the robot could reliably travel along the conductor, transport the warning sphere to the target location, complete the installation process, and safely return to its initial position. The experimental results agreed well with the numerical predictions, confirming the effectiveness of the proposed mechanical design and its practical applicability. The proposed robotic platform provides a safer, more efficient, and cost-effective alternative to conventional maintenance methods while reducing operator exposure to hazardous high-voltage working environments.

Keywords: Aircraft warning sphere; transmission-line maintenance; overhead power transmission; mobile robotic platform; cable-traversing robot; autonomous inspection and maintenance; experimental validation.

Introduction

Electrical power transmission networks have expanded rapidly in recent years owing to the growing demand for reliable electricity and the increasing penetration of renewable energy resources. As transmission corridors continue to extend across mountains, forests, rivers, deserts, and densely populated urban areas, maintaining these infrastructures has become progressively more difficult. The geographical diversity of transmission routes, together with the large scale of

modern power systems, has increased both the technical complexity and the operational cost of inspection and maintenance activities. Because failures in transmission lines may result in widespread power interruptions, substantial economic losses, and serious safety risks, improving maintenance efficiency through intelligent technologies has become an important research direction in modern power engineering [1-3]. Among the numerous maintenance activities carried out on overhead transmission lines, the installation and removal of aircraft warning spheres represents one of the most demanding tasks. These spherical markers, commonly referred to as aerial marker balls or aviation warning markers, are attached to overhead ground wires or conductors to improve their visibility for low-flying aircraft and helicopters operating near airports, highways, rivers, valleys, and mountainous regions. Their use is mandated by aviation safety regulations in many countries and plays an important role in reducing the likelihood of collisions between aircraft and transmission-line infrastructure[4, 5]. At present, as shown in Fig. 1, the installation of aircraft warning spheres mainly relies on helicopters, cranes, or specialized live-line maintenance crews. Although these approaches have proven effective in practice, each of them is associated with significant operational limitations. Helicopter-based installation is expensive, requires experienced pilots and dedicated equipment, and is highly dependent on weather conditions. Crane-assisted operations are only applicable in locations where sufficient road access and working space are available, whereas many transmission lines pass through remote or inaccessible areas. In addition, manual installation near energized conductors exposes maintenance personnel to considerable electrical and mechanical hazards while increasing the duration and overall cost of maintenance operations [2, 3, 6]. These practical limitations have encouraged researchers to investigate robotic solutions for transmission-line maintenance. Progress in robotics, artificial intelligence, machine vision, sensor technologies, autonomous navigation, and intelligent control has made it possible to develop robotic systems capable of operating directly on overhead transmission lines. Compared with conventional maintenance practices, robotic platforms offer several advantages, including reduced exposure of personnel to hazardous environments, improved operational repeatability, lower maintenance costs, and the ability to perform inspection and maintenance tasks with a higher degree of autonomy under challenging field conditions [1-3, 7]



Fig.1. A view of the common methods of installation and replacement of warning spheres

Over the last two decades, the application of robotic technologies to overhead transmission lines has attracted increasing attention from researchers. Early developments were primarily intended to automate routine inspection tasks, reduce maintenance costs, and improve personnel safety. As research progressed, robotic systems evolved from simple inspection devices into more sophisticated platforms capable of performing a wider range of maintenance operations. Based on their primary functions, existing systems can generally be grouped into mobile inspection robots,

maintenance robots, vision-assisted inspection systems, aerial or hybrid robotic platforms, and cooperative multi-robot frameworks.

The earliest transmission-line robots were mainly designed to travel along conductors while overcoming common obstacles such as suspension clamps, spacers, vibration dampers, and insulator strings. One of the pioneering systems was the Expliner robot introduced by Debenest et al. [8], which demonstrated the practicality of robotic inspection on energized overhead ground wires. Building on this concept, Li and Ruan [9] developed an autonomous inspection robot equipped with onboard sensing capabilities for obstacle detection and navigation. Around the same period, Wang et al. [10] proposed a biped line-walking robot whose coordinated mechanical configuration and control strategy improved locomotion stability during operation. These studies established the fundamental principles of robotic mobility on transmission lines and provided the basis for many later developments. Subsequent research focused on improving mobility, obstacle-crossing performance, and the adaptability of robotic mechanisms. Mostashfi et al. [11] introduced a transmission-line inspection robot with enhanced obstacle negotiation capability, while Bahrami [12] proposed a multi-degree-of-freedom robotic system designed to maintain stable motion when traversing complex transmission-line components. Miller et al. [13] further addressed the obstacle-crossing problem by introducing a V-grooved wheel mechanism specifically developed for overhead transmission-line applications. Shruthi et al. [14] later presented a dual-arm robotic platform capable of travelling along both straight conductors and jumper cables, with its mechanical behavior supported through detailed kinematic and dynamic analyses. More recently, research efforts have increasingly concentrated on intelligent control methods. Karagöz et al. [15] developed a neural model reference controller to improve the stability of transmission-line inspection robots, whereas researchers in Japan combined pendulum-based locomotion with anomaly detection techniques to enhance inspection reliability under practical operating conditions [16]. Research has also expanded beyond inspection toward maintenance and repair applications. Song et al. [17] presented a robotic system designed to repair broken strands in overhead ground wires, while Jiang et al. [18] proposed a self-evolving maintenance robot capable of autonomous behavioral planning within complex smart-grid environments. Other robotic platforms have been introduced for specialized maintenance tasks, including transmission-line de-icing [19], conductor sag measurement using integrated sensing technologies [20], and live-line maintenance under extra-high-voltage conditions [3]. Collectively, these developments illustrate the gradual transition of transmission-line robotics from inspection-oriented systems toward platforms capable of actively performing maintenance operations. Alongside the evolution of robotic locomotion, considerable attention has been directed toward improving perception and autonomous decision-making for transmission-line applications. The integration of computer vision, LiDAR (Light Detection and Ranging Sensor), image processing, and artificial intelligence has significantly enhanced the capability of robotic platforms to recognize transmission-line components, identify defects, and operate more reliably in complex environments. Fakhari and Mostashfi [21] reported a field-tested inspection robot that combined visual sensing with an effective obstacle-crossing mechanism under practical operating conditions. Qin et al. [22, 23] further advanced robotic perception by incorporating LiDAR-based object recognition and three-dimensional environmental reconstruction, enabling more reliable detection of transmission-line components and surrounding obstacles. More recently, deep-learning algorithms have become an important part of robotic perception systems, allowing automatic identification of transmission-line accessories with higher accuracy and robustness. As an example, Wu and Fan [24] developed an improved YOLOv8-based, (You Only Look Once Version 8), detection framework for robotic

applications involving aircraft warning spheres, illustrating the growing role of artificial intelligence in transmission-line maintenance. In parallel with these developments, researchers have explored aerial and hybrid robotic platforms to overcome some of the mobility limitations associated with conventional line-travelling robots. Flying-walking systems combine the flexibility of unmanned aerial vehicles with the stability of robots operating directly on conductors, enabling autonomous deployment followed by on-line inspection or maintenance. Chang et al. [25] introduced one of the early concepts in this area, whereas Qin et al. [26] and Li et al. [27] proposed hybrid robotic platforms with improved walking stability under wind disturbances through advanced dynamic modelling and intelligent control strategies. At a broader system level, Fan et al. [28] presented a cyber-physical multi-robot framework for monitoring transmission-line environments, while the European AERIAL-CORE project [7] demonstrated how artificial intelligence, aerial robotics, and digital infrastructure management can be integrated into future power-grid maintenance systems.

Although the literature demonstrates substantial progress in transmission-line robotics, several limitations remain. Most existing robotic platforms have been designed for inspection, condition assessment, vegetation monitoring, de-icing, conductor repair, or the handling of specific transmission-line accessories. Consequently, research has primarily concentrated on issues such as locomotion, obstacle negotiation, navigation, perception, and control. Comparatively fewer studies have addressed robotic systems dedicated to the installation and removal of aircraft warning spheres. Furthermore, the available studies are generally limited to preliminary robotic concepts or individual subsystems, and only a small number provide a complete engineering solution that combines mechanical design, autonomous manipulation, structural assessment, motion verification, and experimental validation within a single platform [4, 5, 24, 29]

Motivated by these limitations, the present work introduces an autonomous mobile robot (Fig.2) specifically designed to perform both the installation and removal of aircraft warning spheres on overhead transmission lines. In contrast to conventional inspection robots, the proposed system integrates a mobile locomotion mechanism, a dedicated gripping unit, a sphere-handling mechanism, and an installation/removal tool into a single maintenance platform capable of operating directly on overhead ground wires. The mechanical integrity of the proposed design is evaluated using finite element analysis, while motion simulations are employed to verify its functional performance before prototype fabrication. A functional prototype is subsequently developed and tested under representative operating conditions to demonstrate the practicality and effectiveness of the proposed robotic system.



Fig. 2. A view of the robot made in this work

The contributions of this study extend beyond the development of a new robotic platform. The proposed system combines autonomous locomotion with a dedicated manipulation mechanism for aircraft warning spheres, supported by structural verification through finite element analysis and mechanical motion simulation. In addition, experimental evaluation of the fabricated prototype

confirms the feasibility of the proposed maintenance approach. The overall framework established in this study provides a practical basis for future autonomous robotic systems intended for the maintenance of overhead transmission-line accessories and contributes to the ongoing development of safer, more reliable, and more intelligent power-grid infrastructure.

The remainder of this paper is organized as follows. Section 3 describes the mechanical design and operating principles of the proposed robot. Section 4 presents the The operational procedure of the proposed robotic system. Section 5 discusses operating principle and numerical simulation, and Section 6 concludes the experimental validation.

3. ROBOT DESIGN

3.1 Overall Mechanical Structure

The proposed robotic platform was developed to autonomously transport, install, and remove aircraft warning spheres on overhead transmission lines while maintaining high mechanical stability, positioning accuracy, and operational reliability. Unlike conventional transmission-line robots, which are primarily intended for inspection and monitoring, the proposed system integrates locomotion, sphere transportation, gripping, installation, and retrieval into a single autonomous platform.

As illustrated in Fig. 3, the robot consists of five principal subsystems: the structural chassis, the locomotion unit, the sphere transfer mechanism, the suspended battery module, and the clamping mechanism. The chassis is fabricated from 2-mm-thick steel sheets using a lightweight grid configuration that provides adequate structural rigidity while minimizing the overall weight of the robot. The manufactured prototype weighs approximately 12 kg, allowing deployment onto the transmission conductor by a single operator without additional lifting equipment.

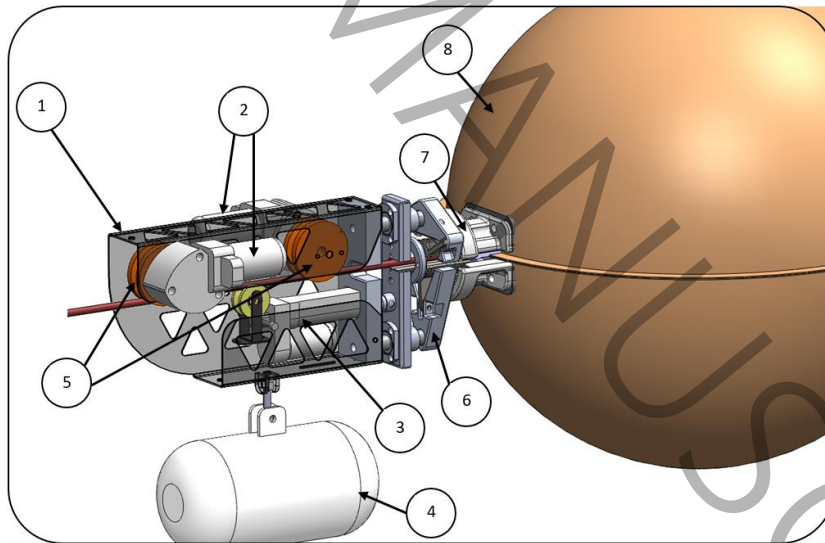


Fig. 3. Main components of the proposed robotic platform. (1) Main chassis, (2) DC geared motors, (3) Linear actuator, (4) Suspended battery module, (5) Drive rollers, (6) Sphere transfer mechanism, (7) Spring-loaded clamp assembly, and (8) Aircraft warning sphere.

Robot locomotion is achieved using two independently driven 12-V DC geared motors, each capable of producing a maximum torque of 15.5 N·m. Motion is transmitted to the conductor through two polyurethane drive rollers positioned on the upper side of the robot. An adjustable guide roller located between the drive rollers increases the contact pressure with the conductor,

improves traction, and minimizes slippage during operation on inclined or vibrating transmission lines.

A linear actuator capable of generating a maximum force of 1000 N provides the driving force required for sphere installation and removal. The actuator transfers motion to the sphere handling mechanism through a rack-and-pinion transmission, enabling precise and repeatable manipulation of the warning sphere.

3.2 Suspended Battery Module

One of the distinguishing features of the proposed robot is the suspended battery module. Instead of being rigidly fixed to the chassis, the battery compartment is connected through a two-degree-of-freedom hinged suspension system equipped with a damping mechanism. Consequently, the battery behaves as a passive pendulum during robot motion.

This configuration significantly lowers the overall center of gravity and improves the robot's static and dynamic stability while travelling on inclined conductors or under lateral wind loading. The suspended battery also generates a gravitational restoring moment that suppresses roll motion around the conductor, helping maintain the robot in a nearly horizontal orientation during operation. Besides improving stability, the damping mechanism absorbs vibrations generated by wheel-conductor interaction, acceleration, deceleration, and wind-induced disturbances. This reduces the transmission of oscillations to the structural frame, sensors, and manipulation mechanism, thereby improving installation accuracy and reducing the likelihood of structural resonance.

The battery enclosure is designed with a streamlined capsule-shaped geometry that reduces aerodynamic drag compared with conventional rectangular housings. Moreover, because the battery simultaneously functions as both the power source and the balancing mass, the need for a separate counterweight is eliminated, reducing the overall weight and simplifying the mechanical design.

3.3 Sphere Handling Mechanism

The sphere handling mechanism is responsible for transporting the aircraft warning sphere together with its dedicated clamp from the robot body to the installation position. As illustrated in Fig. 4, the mechanism is mounted at the front of the robot and is guided by two cylindrical rails equipped with linear bearings to ensure smooth and accurate translational motion.

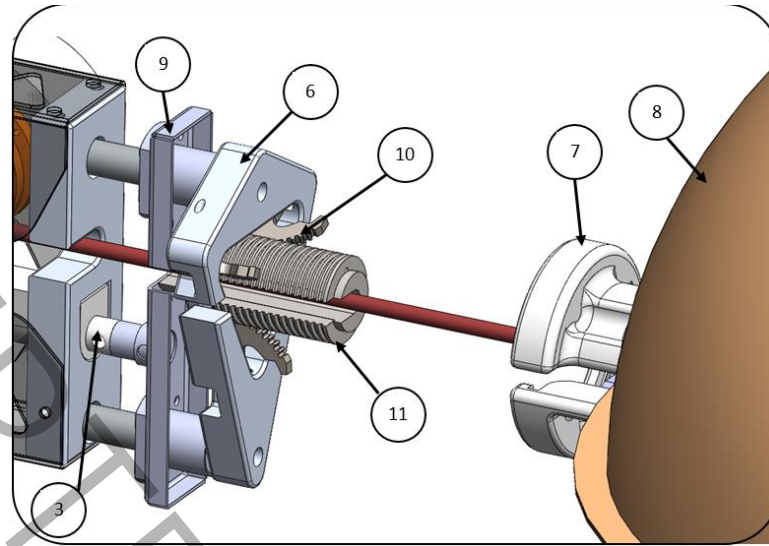


Fig. 4. (3) linear actuator, (6) sphere transfer mechanism, (7) spring-loaded clamp assembly, (8) aircraft warning sphere, (9) linear guide rods, (10) hook-shaped locking element, and (11) cylindrical rack gear.

The mechanism is driven by a rack-and-pinion transmission actuated by the linear actuator. A movable carriage travels along the guide rails, carrying the locking assembly that mechanically interfaces with the warning sphere clamp. Three hook-shaped locking elements are equally distributed around the carriage and engage the clamp during transportation.

When the robot reaches the designated installation location, the actuator advances the carriage, allowing the locking elements to securely engage the clamp. After the sphere has been correctly positioned on the transmission conductor, the carriage retracts, disengaging the locking mechanism while leaving the clamp permanently attached to the conductor. This fully mechanical arrangement eliminates the need for manual handling of the warning sphere and considerably simplifies installation and replacement operations.

3.4 Clamp Design

The clamp assembly, shown in Fig. 5, provides the mechanical connection between the aerial marker sphere and the transmission conductor. The warning sphere consists of two aluminum hemispherical shells permanently connected to the specially designed clamp, allowing both components to be handled as a single assembly during robotic operation.

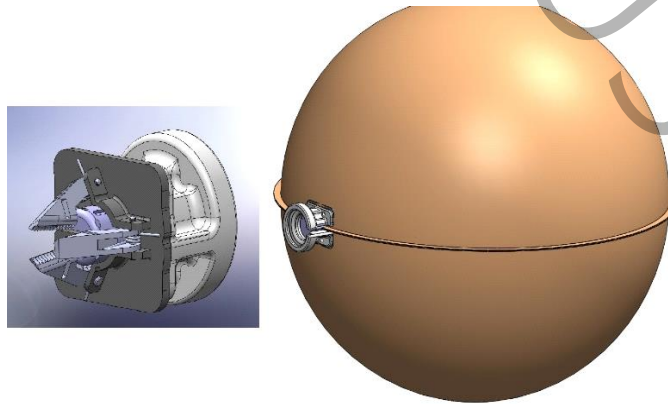


Fig. 5. Clamp and Aerial marker sphere

The internal structure of the clamp is presented in Fig. 6. The mechanism incorporates a cylindrical piston, three compression springs, three gripping fingers, and three torsion springs. Under normal operating conditions, the torsion springs maintain the fingers in a closed position, ensuring secure attachment to the conductor without continuous external actuation.

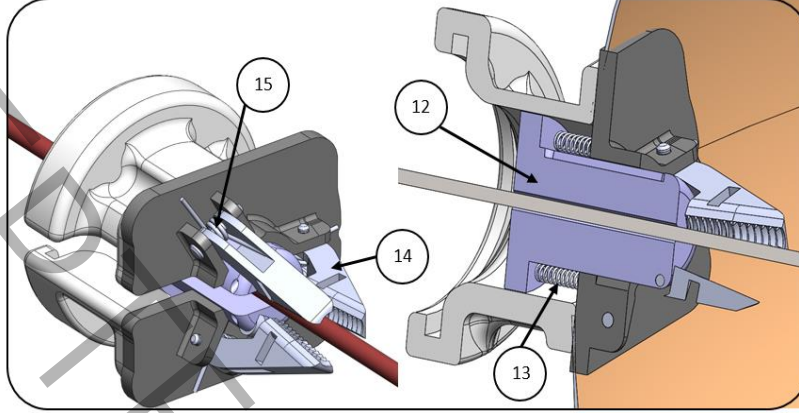


Fig. 6. Inside of clamp

During installation or removal, the linear actuator applies an axial force to the piston through the rack-and-pinion transmission. The forward motion of the piston forces the gripping fingers to rotate outward against the restoring torque of the torsion springs, temporarily releasing the conductor. Once the external force is removed, the compression springs return the piston to its original position, while the torsion springs automatically close the fingers around the conductor. This normally closed configuration provides an inherent fail-safe characteristic, ensuring that the warning sphere remains securely attached even in the event of actuator failure or power interruption. To enhance gripping performance, the contact surfaces of the fingers were machined with shallow grooves, increasing friction while minimizing localized stress concentrations on the conductor.

3.5 Mechanical Design Analysis

1.3.5 Force Analysis of the Clamping Mechanism

To validate the proposed clamping mechanism, an analytical force analysis was performed to determine the required stiffness of both the compression springs and the torsion springs. The corresponding free-body diagram is presented in Fig. 7.

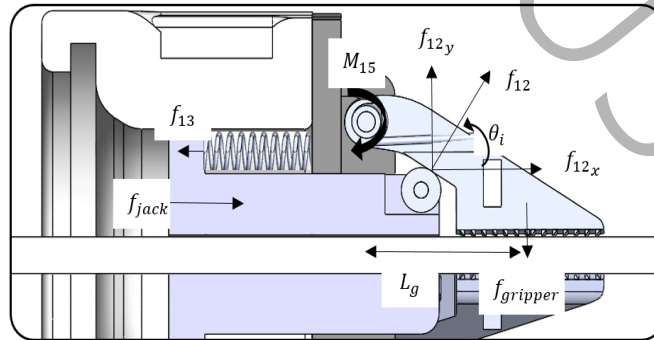


Fig. 7. Force diagram for gripper

The compression springs were designed based on the maximum actuator force of 1000 N and a piston displacement of 7 mm. Using Hooke's law [30], the required spring stiffness was determined from Eqs. 1,2.

$$f_{13} = -(3 \times K_{13}) \Delta x, f_{\text{jack}} = 1000 \text{ N}, \Delta x = 7 \text{ mm} \quad (1)$$

$$K_{13} = 47.61 \frac{\text{N}}{\text{mm}} \quad (2)$$

Similarly, the torsion spring stiffness was calculated from the moment equilibrium of the gripping finger by considering the required gripping force, finger geometry, and angular displacement. The corresponding formulation is presented in Eqs. 3,4.

$$K_{13} = 47.6$$

$$M_{15} = f_{\text{gripper}} \times L - f_{12} \times \frac{1}{2} L = \theta k_{15}, L = 50 \text{ mm}, \theta = 0.349066 \text{ Rad} \quad (3)$$

Therefore, torsion spring constant is:

$$K_{15} = 71 \frac{\text{N.m}}{\text{rad}} \quad (4)$$

The calculated spring constants provide sufficient gripping force to securely retain the warning sphere under operational loading conditions, including wind loads, conductor vibration, and external impacts, while ensuring reliable release during robot-assisted installation and replacement. Consequently, the proposed mechanism achieves an effective balance between gripping reliability, structural durability, and actuator force requirements.

2.3.5 Dynamic Stability Analysis

Besides the clamping mechanism, the overall dynamic stability of the robot is strongly influenced by the configuration of the suspended battery module. In the proposed design, the main battery is mounted beneath the robot body through a two-degree-of-freedom hinged support equipped with a damping mechanism. This arrangement enables the battery to function simultaneously as the electrical power source and as a passive stabilizing mass, eliminating the need for a separate counterweight. Positioning the battery beneath the chassis lowers the overall center of gravity of the robot, thereby reducing the overturning moment generated by gravitational and lateral forces during locomotion, obstacle negotiation, and exposure to crosswinds. As a result, the robot maintains greater stability while travelling along inclined conductors and passing transmission-line accessories. Another important benefit of the suspended battery is the suppression of roll motion about the conductor. Because the battery behaves as a suspended pendulum, any rotational displacement of the robot generates a gravitational restoring torque that naturally opposes torsional motion. Consequently, the robot remains in a nearly horizontal orientation, improving the performance of the locomotion system, sensors, and sphere installation mechanism. The integrated damping mechanism further improves the robot's dynamic response by dissipating vibration energy generated by wheel-conductor interaction, acceleration and deceleration, and wind-induced disturbances. This reduces vibration transmission to the robot body, minimizes the possibility of structural resonance, and improves positioning accuracy during installation and removal operations. From an aerodynamic perspective, the suspended battery slightly increases the projected frontal area of the robot. However, the damping mechanism effectively dissipates the kinetic energy introduced by turbulent airflow and crosswinds, preventing the development of large-amplitude oscillations and reducing the risk of aeroelastic instabilities such as galloping. Overall, the suspended battery configuration improves the stability of the robotic platform while reducing its overall weight by eliminating the need for an additional counterweight. Preliminary field experiments demonstrated satisfactory anti-roll performance and vibration suppression during robot operation. Future work will include multibody dynamic simulations using MSC

ADAMS and finite element analyses in ANSYS to optimize the battery position, suspension geometry, and damping characteristics under various operating conditions.

4. Operating Principle

The operational procedure of the proposed robotic system consists of four sequential stages: deployment, transportation, installation (or removal), and retrieval. The entire operation is performed using a single mobile robotic platform equipped with a dedicated clamping mechanism for handling the aircraft warning sphere.

Prior to operation, the robot is manually placed on the transmission conductor by an operator located on the transmission tower. At the starting point, the warning sphere together with its clamp is mechanically connected to the robot through the hook-based locking mechanism described in the previous section. After the mechanical connection is verified, the robot is ready for remote operation. A second operator located on the ground remotely controls the robot using a wireless controller. The robot travels along the transmission conductor while carrying the warning sphere toward the predetermined installation location. The locomotion system enables stable movement on inclined conductors while the suspended battery module continuously maintains the center of gravity below the conductor, improving stability throughout the travel path. Once the robot reaches the installation point, the linear actuator activates the quick-release mechanism. The piston inside the clamp temporarily opens the gripping fingers, allowing the clamp to be accurately positioned around the transmission conductor. As the actuator retracts, the torsion springs automatically close the gripping fingers, securely attaching the warning sphere to the conductor. Immediately after successful attachment, the hook mechanism disengages from the clamp, leaving the warning sphere fixed at the desired location. Following completion of the installation process, the robot travels back along the conductor to the initial deployment point using the same locomotion mechanism. The robot is then manually removed from the transmission line by the operator located on the tower. The same operating sequence can also be employed for the removal of existing warning spheres. In this case, the robot approaches the installed sphere, mechanically engages the clamp using the hook mechanism, releases the gripping fingers through the linear actuator, retrieves the warning sphere, and transports it back to the starting location. The complete installation and removal procedures require only two operators: one operator is responsible for placing and retrieving the robot from the transmission line, while the second operator remotely controls the robot from ground level throughout the operation. This operating procedure substantially reduces personnel exposure to hazardous working environments and eliminates the need for helicopters, cranes, or prolonged transmission-line outages under suitable operational conditions.

5. Operating Principle and Numerical Simulation

5.1 Ball Installation and Separation Procedure

The proposed robotic platform performs aircraft warning sphere installation and removal through a fully mechanical interaction between the robot-mounted transfer mechanism and the dedicated clamping assembly attached to the sphere. Unlike conventional approaches that require direct manipulation of the warning sphere by operators at elevated locations, the developed system enables transportation, positioning, attachment, and release operations through a controlled sequence performed by the robot. The interaction mechanism between the robot and the clamp is illustrated in Fig. 8. The front section of the clamp is equipped with a specially designed groove that serves as the engagement interface for the hook-shaped locking elements mounted on the robot. When the robot approaches the clamp from the rear side, the linear actuator activates the internal transmission mechanism, converting the actuator's linear motion into the synchronized

forward movement of three hook-shaped elements. These hooks enter the corresponding groove on the clamp body and establish a mechanical connection between the robot and the warning sphere assembly.

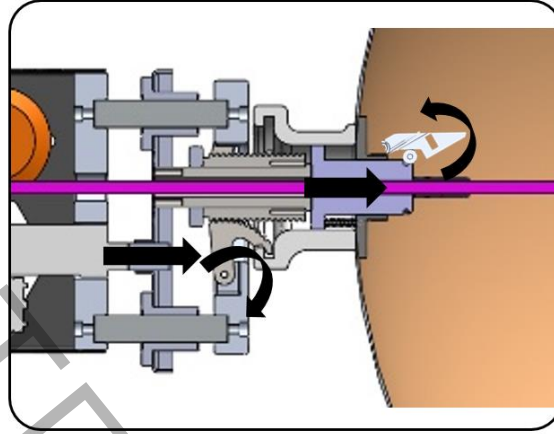


Fig. 8. Mechanism function

After the mechanical engagement is completed, the same actuation system drives the internal piston located inside the clamp. The forward displacement of the piston overcomes the preload of the torsion springs and temporarily releases the three gripping fingers from the transmission conductor. As a result, the clamp and the attached warning sphere are transferred from a fixed position on the conductor to the robot mechanism, allowing the complete assembly to be transported along the transmission line.

During transportation, the warning sphere remains securely connected to the robot through the hook-based locking mechanism, while the locomotion system moves the robot along the conductor toward the required installation location. After reaching the target position, the installation process is performed by reversing the previous sequence. The linear actuator retracts, causing the hook-shaped elements to disengage from the clamp groove. Simultaneously, the piston returns to its initial position, allowing the torsion springs to restore the gripping fingers around the conductor. The clamp therefore returns to its default locked configuration and remains attached to the transmission line, while the robot becomes separated from the sphere assembly and can continue its movement or return to the initial deployment point. The normally closed configuration of the clamp provides an inherent safety advantage because the sphere remains secured to the conductor in the absence of actuator force or during unexpected power interruption.

The proposed mechanism eliminates the need for manual handling of warning spheres during installation and removal operations. Furthermore, the integration of the transfer mechanism and the spring-loaded clamp enables repeated attachment and separation cycles with minimal operator intervention, which improves operational safety and reduces the complexity associated with conventional maintenance procedures.

5.2 Center of Gravity and Stability Analysis

The stability of the proposed robotic platform is strongly influenced by the distribution of its mass components, particularly the position of the battery module and the relative location of the center of gravity with respect to the transmission conductor. Therefore, a mass property analysis was performed using SolidWorks Motion to evaluate the static equilibrium and potential rotational tendency of the robot during operation.

The complete three-dimensional model of the robotic platform, including the main chassis, locomotion system, sphere handling mechanism, suspended battery module, and clamping assembly, was imported into the simulation environment. The material properties and masses of individual components were assigned according to the specifications of the manufactured prototype. This approach allowed the actual mass distribution of the robot to be considered in the stability evaluation.

The calculated mass properties and center-of-gravity position obtained from the simulation are presented in Fig. 9. The total mass of the developed prototype was approximately 12 kg, and the calculated center of gravity was located below the transmission conductor and approximately aligned with the longitudinal axis of the robot. This configuration reduces the tendency of the robot to rotate around the conductor by minimizing the lateral offset between the gravitational force line and the conductor axis.

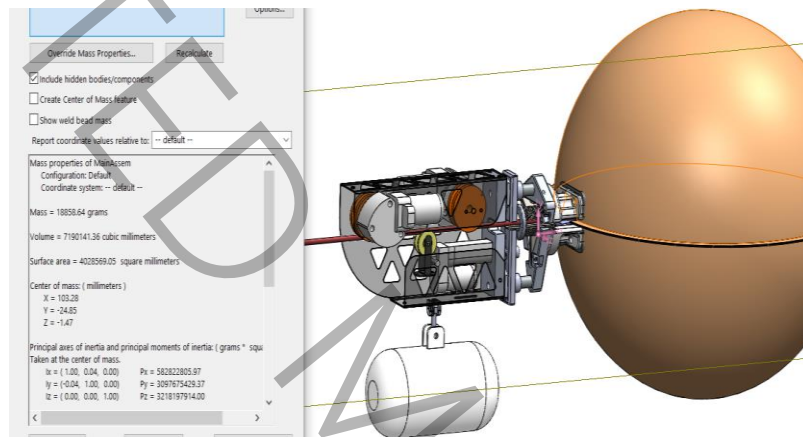


Fig. 9. Mass properties evaluation diagram obtained from SolidWorks software

A major contribution to the stability performance is provided by the suspended battery module. Unlike conventional rigidly mounted battery configurations, the proposed design places the battery beneath the main chassis through a hinged connection, allowing it to act as a passive stabilizing mass. By maintaining the center of mass below the conductor, the suspended battery generates a restoring moment against rotational disturbances caused by uneven loading, robot movement, or external environmental forces.

The position of the center of gravity is particularly important during operation on inclined conductors, where gravitational components can introduce additional overturning moments. The proposed configuration reduces these effects and improves contact stability between the drive rollers and the conductor. Consequently, the probability of wheel slippage, loss of alignment, and unwanted torsional rotation around the conductor is minimized.

The calculated mass distribution was also considered together with the weight of the warning sphere and its clamp assembly to ensure that the robot remains dynamically balanced while transporting the payload. The results indicate that the selected structural arrangement provides an appropriate balance between mechanical compactness, payload capability, and operational stability.

5.3 Wind Load Simulation

Since overhead transmission lines are exposed to variable outdoor environmental conditions, wind loading represents one of the most important external disturbances affecting the stability of cable-traversing robotic systems. Therefore, the influence of lateral wind forces on the proposed robot was investigated through numerical simulation under a conservative loading condition.

In this analysis, a steady wind velocity of 20 m/s was applied to the complete robotic model. This value was selected to represent severe environmental conditions that may occur during transmission-line operation. The wind direction was considered perpendicular to the robot travelling direction, corresponding to one of the most critical loading scenarios in terms of generating a rotational moment around the conductor.

The applied wind force and the coordinate system considered in the simulation are illustrated in Fig. 10. Due to the suspended configuration of the battery module, the battery behaves as a passive pendulum and contributes to the dynamic stability of the robot. When the robot is subjected to lateral wind forces, the suspended mass generates a restoring moment that opposes the rotational tendency of the main body. In addition, the capsule-shaped geometry of the battery enclosure reduces the aerodynamic resistance compared with conventional rectangular battery housings.

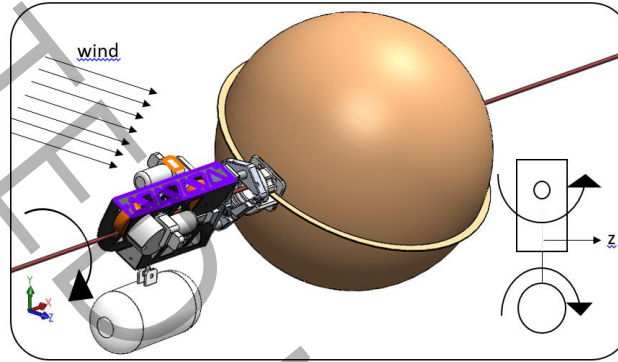


Fig.10. Wind force and coordinate system

The interaction between the aerodynamic force acting on the robot body and the restoring effect of the suspended battery determines the final equilibrium position of the system. Although the suspended battery may slightly increase the overall projected area of the robot, its stabilizing effect is dominant because the generated restoring torque reduces the amplitude of lateral oscillations and prevents excessive rotation around the conductor.

The resulting displacement of the robot center of gravity along the lateral Z-axis is presented in Fig. 11. Under the considered worst-case wind loading condition, the maximum displacement of the center of gravity was approximately 10 mm.

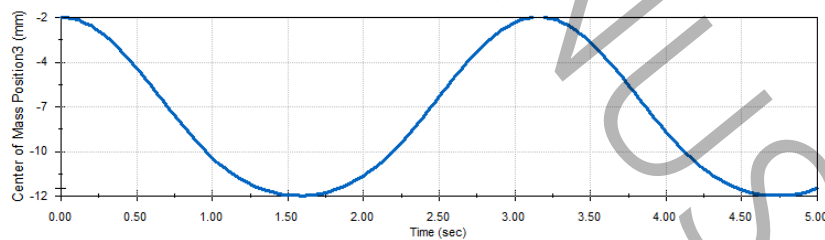


Fig. 11. Displacement of the center of gravity along the Z-axis

The obtained displacement indicates that the wind-induced motion remains within an acceptable range and does not compromise the contact between the drive rollers and the conductor. Although a small oscillatory response was observed during the simulation, the amplitude was insufficient to affect the robot's operational stability or the accuracy of the sphere installation mechanism.

It should be noted that the simulation was intentionally performed under a conservative assumption of continuous wind application from a constant direction. In real transmission-line environments, wind conditions are generally unsteady, with continuous variations in magnitude and direction. Therefore, the actual dynamic response of the robot is expected to be less severe than the simulated worst-case condition.

Overall, the wind-load analysis confirms the effectiveness of the suspended battery concept as a passive stabilization strategy. By lowering the center of gravity and generating a restoring moment against lateral disturbances, this design improves the reliability of robot operation under realistic outdoor conditions.

5.4 Motion Simulation

The mobility performance of the proposed robotic platform was evaluated through dynamic simulation to investigate its capability of travelling along overhead conductors under demanding operating conditions. Since the robot is required to move on inclined transmission lines while carrying the warning sphere and its clamping assembly, the simulation was performed under a challenging scenario representing a high mechanical loading condition.

A simplified three-dimensional model of the robot was developed for the simulation. Nonessential components and minor geometric details that had negligible influence on the dynamic response were removed in order to reduce computational complexity while maintaining the primary mechanical characteristics of the system, including the chassis mass, drive mechanism, roller contact conditions, and suspended battery module.

To evaluate the fundamental mechanical performance of the proposed robot, several simplifying assumptions were adopted in the present simulation. The robot body and the transmission conductor were modeled as rigid bodies, while the conductor was assumed to be locally straight over the simulated travel distance. Cable sag, conductor vibration, structural flexibility, wheel slip, gearbox efficiency losses, and motor control dynamics were neglected because the objective of this preliminary analysis was to evaluate the mechanical feasibility of the locomotion system under representative worst-case loading conditions rather than to develop a complete dynamic model. Rolling friction between the polyurethane rollers and the conductor was assumed to remain constant throughout the simulation. These assumptions significantly reduce computational complexity while preserving the accuracy required for evaluating the robot's mobility and stability. More comprehensive multibody dynamic analyses incorporating conductor flexibility, environmental disturbances, and advanced closed-loop control algorithms will be investigated in future work.

The most critical mobility condition was considered as the robot travelling upward along a conductor inclined at 30° relative to the horizontal plane. This condition represents one of the most demanding cases because the drive system must overcome both rolling resistance and the gravitational component acting against the direction of motion.

The simulation was performed over a period of 8 s. Initially, the robot travelled on a horizontal conductor, and after approximately 1 s, it entered the inclined section. A driving torque of $15 \text{ N}\cdot\text{m}$ was simultaneously applied to both drive rollers, corresponding to the maximum torque capability of the selected DC geared motors.

The simulation results are presented in Fig. 12. The figure includes the variation of the reaction force acting on the drive rollers and the angular kinetic energy during the robot motion.

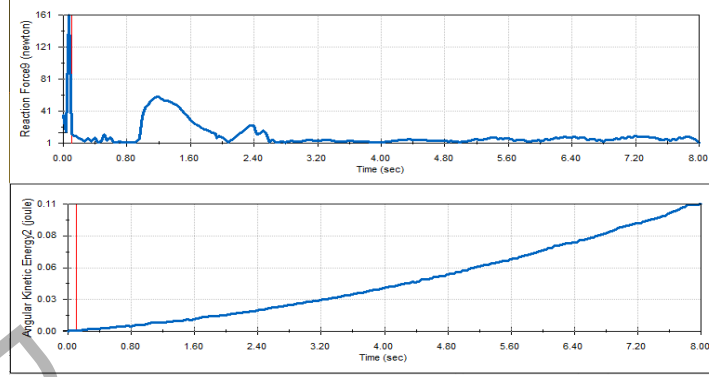


Fig. 12. Simulation results: (a) reaction force and (b) angular kinetic energy of rollers

As shown in Fig. 12(a), the initial stage of motion requires a relatively high reaction force due to the static friction between the rollers and the conductor surface. This force decreases after the robot starts moving and reaches a stable condition. A second increase in the reaction force occurs when the robot encounters the 30° inclined section, where additional traction is required to overcome the gravitational resistance. After passing this transition region, the reaction force gradually stabilizes, indicating that continuous motion can be maintained without loss of contact.

The angular kinetic energy of the rollers during the motion is illustrated in Fig. 12(b). The energy increases during the acceleration phase and while the robot climbs the inclined section. After reaching a steady travelling condition, the variation becomes limited, indicating that the drive system operates within a stable dynamic regime.

The simulation results confirm that the selected geared motors provide sufficient torque to maintain traction under unfavorable operating conditions. Furthermore, the estimated energy consumption obtained from the roller kinetic energy analysis provides an indication of the required battery capacity for completing a typical installation cycle. These results demonstrate that the proposed locomotion system can provide reliable movement along inclined transmission conductors while transporting the warning sphere assembly.

The current version of the developed robot is operated via manual remote control. An operator controls the robot's movement and speed using a wireless remote controller while visually monitoring its operation. However, due to the complex dynamics of the system (especially the pendulum motion of the suspended battery-damper unit and the possibility of torsional rotation around the wire), we are aware of the limitations of pure manual control. In the next phase of this research, we plan to implement an advanced control system, specifically a Model Predictive Controller (MPC) or an adaptive control scheme. This future controller will predict the robot's dynamic behavior, including the effects of the hanging battery, wind disturbances, and obstacles, to automatically adjust motor commands for smoother and more stable movement. Currently, the manual remote control is augmented with basic safety features such as: Real-time current and voltage monitoring Emergency stop command Speed limiting to prevent excessive oscillations We acknowledge the reviewer's valuable comment and consider the development of a predictive autonomous control system as a high priority for future work to enhance the robot's performance and safety in real power line conditions.

6. Experimental Validation

To verify the practical feasibility of the proposed robotic platform, a full-scale prototype was fabricated and evaluated under representative transmission-line operating conditions. The experimental investigation was primarily intended to validate the mechanical functionality of the locomotion system, the sphere transfer mechanism, and the clamping assembly developed in this

study. The robot was manufactured according to the design specifications presented in the previous section and assembled using commercially available mechanical and electrical components. Particular attention was given to ensuring that the prototype dimensions, structural rigidity, and weight distribution were consistent with those used in the numerical simulations. This approach enabled a direct comparison between the predicted behavior and the experimental observations. Prior to field deployment, the complete mechanical system, including the drive mechanism, suspended battery module, and sphere handling assembly, was inspected and tested under laboratory conditions to verify the proper operation of all moving components. After confirming the mechanical integrity of the system, the robot was deployed onto a transmission-line conductor for functional evaluation. During the experiments, the robot was manually placed on the conductor by an operator positioned on the transmission tower, while a second operator remotely controlled its motion using a wireless control unit from a safe location. The current prototype was intentionally designed as a remotely operated system because the primary objective of this study was to validate the proposed mechanical concept before implementing autonomous navigation and control algorithms. The experimental procedure consisted of transporting the aircraft warning sphere together with its dedicated clamp to a predetermined installation location. The robot travelled smoothly along the conductor while maintaining continuous contact between the drive rollers and the cable. No significant wheel slippage, derailment, or excessive oscillation was observed throughout the travelling sequence.

After reaching the designated position, the sphere transfer mechanism successfully engaged the clamping assembly and completed the installation sequence described in Section 5.1. Following attachment of the clamp to the conductor, the robot disengaged from the warning sphere and safely returned to its initial deployment point using the same travel path.

The average duration required for one complete installation cycle, including travelling to the installation location, performing the installation procedure, and returning to the starting position, was approximately 15 min. The mechanical components operated reliably throughout the experiments, and no structural damage or functional failure was observed during repeated installation and removal operations.

The developed prototype was successfully evaluated under real transmission-line conditions as part of an industrial maintenance project. The complete operational sequence, including deployment, transportation of the warning sphere, installation, disengagement of the transfer mechanism, return to the starting point, and sphere removal, was successfully completed during all field trials. The average duration of a complete installation cycle was approximately 15 min, and all installation and removal operations were completed successfully without mechanical failure, derailment, or loss of stability. Furthermore, the prototype was experimentally tested on both de-energized and energized transmission lines under the supervision of experts from the regional power utility, demonstrating the practical applicability of the proposed system for real maintenance operations.

The experimental observations demonstrated good agreement with the numerical simulation results presented in Sections 5.2–5.4. In particular, the suspended battery module effectively improved the stability of the robot during movement, while the drive system generated sufficient traction to negotiate inclined conductor sections without interruption. These results confirm the practicality of the proposed mechanical design for transmission-line maintenance applications

7. Discussion

The results of both the numerical analyses and the experimental investigations demonstrate that the proposed robotic platform provides a practical solution for the installation and removal of

aircraft warning spheres on overhead transmission lines. The agreement between simulation and field observations confirms the validity of the proposed mechanical design and the effectiveness of the developed operating mechanism. One of the main innovations of the proposed robot is the integration of a dedicated sphere-transfer mechanism with a spring-loaded clamping system. Unlike most existing transmission-line robots, which are primarily designed for inspection or monitoring tasks, the developed platform is capable of transporting, positioning, installing, and removing aircraft warning spheres while travelling directly on the conductor. This capability considerably reduces the need for manual intervention during maintenance operations and improves personnel safety. Another important contribution is the suspended battery module, which simultaneously functions as the primary power source and as a passive stabilizing element. Positioning the battery below the main chassis lowers the overall center of gravity and generates a restoring moment that reduces the tendency of the robot to rotate around the conductor. The numerical results obtained from the stability and wind-load analyses demonstrated that this configuration effectively limits lateral oscillations under unfavorable environmental conditions. The field experiments further confirmed that the suspended battery improves the overall balance of the robot without requiring additional balancing mechanisms or counterweights. The motion simulation also verified that the selected drive system provides sufficient traction to overcome the gravitational forces encountered on inclined transmission conductors. The predicted reaction forces and energy consumption were consistent with the observed performance of the manufactured prototype, indicating that the selected motors and battery capacity satisfy the operational requirements of the proposed application. Compared with conventional installation techniques that rely on helicopters, cranes, or transmission-line outages, the proposed robotic platform offers several practical advantages. The system reduces maintenance costs, shortens installation time, minimizes human exposure to hazardous environments, and provides the possibility of performing maintenance operations while preserving service continuity when permitted by operational regulations. Despite these promising results, several limitations remain. The current prototype is operated through a wireless remote-control system, and the navigation process still depends on human supervision. Furthermore, the experimental validation focused primarily on evaluating the mechanical performance of the proposed platform under representative operating conditions. Additional investigations under a wider range of environmental conditions, including stronger wind loads, conductor vibration, and obstacle-crossing scenarios, are required before large-scale industrial deployment. Another limitation concerns the control strategy. Although remote operation was considered appropriate for validating the mechanical concept, autonomous operation will require a more advanced control architecture capable of compensating for nonlinear dynamic effects introduced by the suspended battery, wind disturbances, and variations in conductor geometry. Future studies will therefore focus on the implementation of Model Predictive Control (MPC) and adaptive control algorithms to improve trajectory tracking, disturbance rejection, and overall operational stability. The integration of vision-based localization, onboard sensing, and intelligent path-planning techniques is also expected to enhance the autonomy and reliability of the proposed robotic platform. Overall, the presented results demonstrate that the proposed robot represents a promising step toward intelligent robotic maintenance of overhead transmission networks. By combining a novel sphere-handling mechanism with an inherently stable mechanical configuration, the developed platform provides a practical foundation for future autonomous maintenance systems capable of operating safely and efficiently on energized transmission lines.

8. Conclusion

This paper presented the design, development, numerical evaluation, and experimental validation of a mobile robotic platform for the installation and removal of aircraft warning spheres on overhead power transmission lines. The proposed system was developed to provide a safer and more efficient alternative to conventional installation methods that rely on helicopters, cranes, or scheduled transmission-line outages. The robot integrates a cable-traversing locomotion system, a dedicated sphere transfer mechanism, a spring-loaded quick-release clamp, and a suspended battery module that simultaneously serves as the power supply and a passive stabilization element. This integrated mechanical design enables the robot to transport the warning sphere, perform controlled installation and removal operations, and safely continue its movement along the transmission conductor. Mechanical analysis of the clamping mechanism was carried out to determine the required stiffness of both the compression and torsion springs, ensuring reliable attachment of the warning sphere while allowing repeated installation and removal operations. Numerical simulations demonstrated that the proposed configuration provides stable operation under demanding environmental conditions. The center-of-gravity analysis confirmed that positioning the suspended battery below the conductor significantly improves static and dynamic stability. Furthermore, wind-load simulations indicated that the robot remains stable under a lateral wind velocity of 20 m/s, with a maximum lateral displacement of approximately 10 mm. Dynamic simulations also verified that the selected drive system provides sufficient traction and torque to negotiate inclined transmission conductors while carrying the warning sphere assembly. A full-scale prototype was successfully fabricated and experimentally evaluated under representative operating conditions. The experimental results confirmed the effectiveness of the proposed locomotion, transfer, and clamping mechanisms, demonstrating smooth movement along the conductor, reliable sphere installation and removal, and stable operation throughout the complete installation cycle. The observed behavior was consistent with the numerical predictions, confirming the validity of the proposed mechanical design.

Compared with conventional maintenance techniques, the proposed robotic platform offers several practical advantages, including improved personnel safety, reduced maintenance costs, lower dependence on specialized equipment, and the potential to perform maintenance operations without interrupting power transmission. These features make the proposed system a promising solution for future robotic maintenance of overhead transmission networks.

Future research will focus on the integration of autonomous navigation, intelligent localization, obstacle-crossing capability, advanced sensing technologies, and predictive control algorithms to further improve the operational efficiency and autonomy of the robotic platform under real transmission-line conditions.

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Competing interests: The authors declare that they have no conflict of interest.

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Author Contribution statement

Our contribution is as follows, Amir Pouyan Torabideh, Mostafa Rouzbeh and alireza Ostadi are the authors of the article and the original researcher with a 50% share, and Dr. Iman mohammadi is the supervisor and as a data analyst with a share of 50%.

Funding

I declare that I have no significant competing financial, professional, or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.