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ORIGINAL ARTICLE

A Review of Line Suspended Inspection Robots for Power Transmission Lines

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Abstract
Inspection and maintenance of power transmission lines are crucial in terms of providing uninterrupted power for the consumers. Inspection and maintenance of transmission lines passing through areas that are difficult to reach and pass through are usually carried out by workers or with the help of helicopter. These methods are not effective in terms of time, energy, safety, economy, and efficiency. Transmission line inspection robots can perform this task safely, efficiently, economically, quickly with the least risk. In this study, theoretical and experimental studies on line suspended power transmission line inspection robots in the literature are examined. Details of robots with different mechanisms are presented. Robots, which perform the line inspection process with the help of cameras and sensors, can also overcome various obstacles on the line. Produced robot prototypes have been tested in the field and laboratory environment. In this paper, these robots are grouped as those that move on live lines and ground wires. In addition, the advantages and disadvantages of robots have been determined depending on the line they move. Looking at the studies in the literature, it can be said that the inspection of power transmission lines with the help of robots is the most appropriate method compared to traditional methods.

Keywords Power transmission line · Inspection robot · Transmission line inspection · Review · Mobile robot · Robot control

1 Introduction

Electrical energy, an indispensable element of daily life and business, is a significant indicator of civilisation and development today. Simultaneously, electricity is one of the most critical factors in developing countries, as it is one of the most widely consumed forms of energy worldwide. The electrical energy produced at medium voltage (1–35 kV) is amplified using power transformers and transported to demand points via high voltage power transmission lines [1]. Electrical energy is transported from the point where it is produced to the point where it is consumed by Power Transmission Lines. Electrical energy is transported from the point of production to the point of consumption through power transmission lines, utilising wires of various types and sections at different voltage levels. The selection of wire types and sections depends on the amount of energy to be transported and the distance between the production and consumption centres. With the proliferation and growth of production and consumption centres, these interconnect through power transmission lines.

The transmission lines require regular inspection and monitoring to ensure their safe and stable operation [2]. The objective is to minimise permanent downtime, prevent facility damage, and reduce potential malfunctions. Annual and periodic inspection and maintenance programs are developed for power transmission lines, considering factors such as regional conditions, natural surroundings, and their

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significance in the system [3]. Transmission lines, which facilitate transportation, traverse challenging and inaccessible areas like highlands, deserts, water bodies, and forests, covering long distances. Given these demanding environments, it becomes apparent how difficult it is to maintain, monitor, and inspect power transmission lines. Despite these challenges, it is crucial to assess the condition of cables, towers, and accessories along the transmission line and mitigate any risks that could impede the efficient transmission of electrical energy [1].

Line inspection involves components such as insulators, dampers, conductors, spacers, and clamps. Insulators can develop cracks due to air changes and arcs, directly impacting the safety of transmission lines as they provide electrical isolation and mechanical support to the system. Conductors may experience thinning, or punctures caused by leakage currents and corona events [4, 5]. Regular inspections should be conducted to identify the parts that require maintenance. Cost, time, efficiency, and human safety are critical during the inspection process. Detecting and localising faults in transmission equipment is crucial for electricity transmission and distribution companies to minimise maintenance costs and prevent power outages [6, 7]. Maintenance costs include employee wages, protective clothing, training, tools, equipment, energy cut fees, accommodation, transportation, and other expenses. Inspections of power transmission lines are scheduled annually, and each team member records specific points to consider during the inspection. The collected information guides the determination of maintenance requirements [3]. Therefore, power transmission lines should be inspected using the most appropriate methods.

Two methods have been employed for inspecting power transmission lines thus far. The first method involves manual inspection by workers on the ground using telescopes. In some cases, workers must utilise gondolas suspended from overhead ground wires or climb metal towers (Fig. 1). This way of working has several drawbacks, including high labour intensity, lengthy inspection cycles, high costs, and risks to personal safety. Ensuring inspection quality in challenging environments such as highlands, meadows, and forests is particularly difficult. The second method entails checking power transmission line equipment using helicopters equipped with inspection devices such as thermal infrared imagers and visible light cameras. Helicopters offer advantages in terms of greater efficiency for inspections conducted in high-altitude, cold, and non-dedicated landing areas. However, this method suffers from high costs and decreased inspection quality under adverse weather conditions [8, 9].

Power transmission line inspection robots have emerged as an alternative to replace the methods above. Research on these robots commenced in the late 1980s and has made significant progress due to advancements in mobile robotics technology. Scientific research institutions worldwide, including Japan, Canada, the United States, China, Thailand, and others, have actively contributed to developing power transmission line inspection robots [12].

In 1991, Sawada et al. from Japan were among the first researchers to develop and design a practical mobile power transmission line inspection robot. Over the following years, the field of power transmission line inspection robots has become the research topic of many scientists and researchers [13, 14]. One of the common points of most previous studies up to a certain period (approximately the 2000s) is that the robots move on the ground wire (ground conductor), which is located a few meters above the transmission lines and supported at the tops of the towers. In this case, detailed inspection of transmission lines requires powerful cameras and specialised control methods. Therefore, researchers began exploring the possibility of robots moving directly on live transmission lines to gather more detailed data [15]. Over

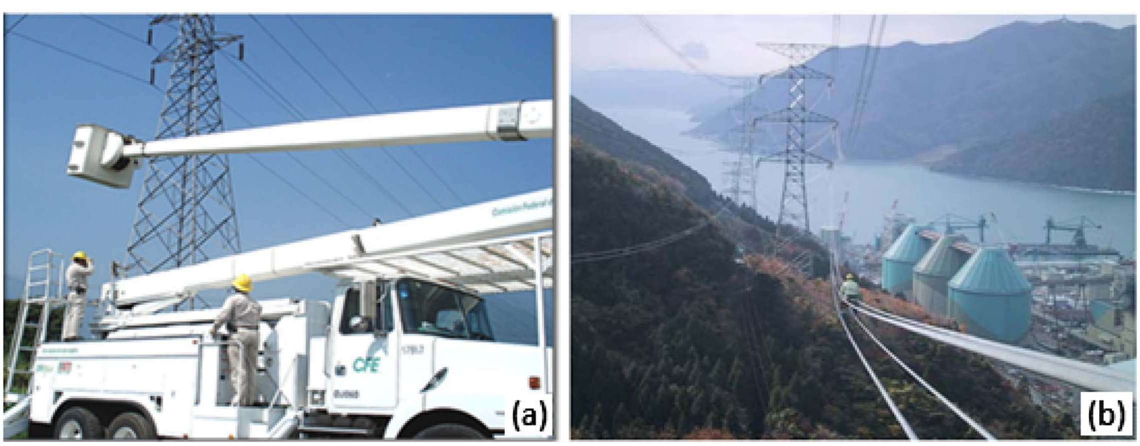


Fig. 1 **a** Workers checking with climbing equipment [10] **b** Workers performing preventive maintenance on transmission lines suspended tens of meters above the ground [11]

time, researchers have introduced a series of power transmission line inspection robots. Power line inspection and maintenance already benefit from developments in mobile robotics, which can reduce the potential risk to maintenance crews (e.g., live work), reach challenging access spans (e.g., river crossings), perform tedious labour faster, and decrease costs [16].

Power transmission line inspection robots are required to be capable of operating and monitoring autonomously along the lines and navigating and overcoming various obstacles encountered along the way [17, 18]. These obstacles include dampers, isolators, clamps (such as tension and suspension clamps), spacers, splicing sleeves, towers, and other electrical equipment. While some obstacles may be small and relatively easy to overcome, others are larger and present more significant challenges. A few obstacles are given in Fig. 2. Besides obstacle navigation, the robot should be able to move swiftly along the line, halt when it encounters an obstacle, and maintain stability throughout the obstacle-crossing process [13, 19, 20].

Power transmission line inspection robots are utilised to conduct inspections of transmission lines in a faster, more efficient, safer, and cost-effective manner compared to traditional inspection techniques mentioned earlier. Generally, these robots are remotely operated by humans stationed in a ground control centre using a radio controlled system [13, 21]. In robots, which are gradually replacing human workers by assuming the inspection of power transmission lines, various approaches have been recorded for obstacle crossing, from multi-arm structures to gibbon-inspired crawling structures. Most line inspection robots are suspended on the transmission line and cause a payload on the line. Therefore, weight is a critical factor for line inspection robots. Limiting weight is challenging as robots are powered by motors and carry cameras. In addition, electric motors and their components must have protective measures to withstand and operate in extreme electromagnetic conditions in the environment [22, 23]. Wind can cause swaying in transmission lines, negatively impacting the inspection process. Hence, the robots must be resistant to oscillations and capable of performing inspections under such conditions [24–26]. Ongoing studies focus on achieving full automation of the inspection process, reducing weight, enhancing operability in electromagnetic field environments, and improving obstacle-crossing capabilities.

The primary purpose of this article is to review and compile line suspended robots explicitly designed for power transmission line inspection. Previous studies have conducted various reviews on inspection robots; [9, 13, 16, 27–33]. In this study, line suspended robots in the literature are categorised based on the characteristics of the lines they move and are presented in chronological order within their respective categories. The aim is to identify existing robots, examine their features, and illustrate the advancements in power transmission line inspection brought about by these robots. Thanks to the prepared tables, summary information about suspended inspection robots in the literature is provided. Such a grouping has not been done in previous

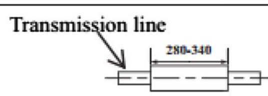
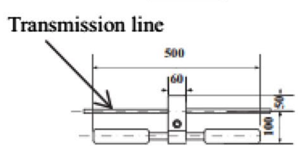
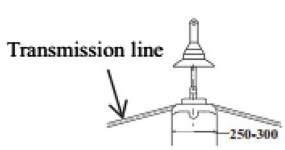
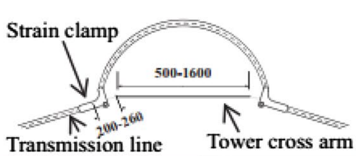
Name	Traversability	Horizontal angle	Parameters and installation situation /mm	Photo
Splicing sleeve	Can be crossed upside	No		
Vibration damper	Can be crossed upside	No		
Suspension clamp	Cannot be crossed upside	No		
Strain clamp	Cannot be crossed upside	Maybe		

Fig. 2 Some obstacles in the transmission line and their characteristics [20]

reviews, and power transmission line inspection robots have been listed more clearly thanks to the grouping made in this study. Additionally, some control algorithms used in such robots and the challenges of robots are mentioned, and it is aimed to give an idea for the studies to be done on this subject.

The article is organised as follows: In the first section, general information about power transmission line inspection robots is given. The second part briefly details how some inspection robots in the literature are controlled. In the third section, the primary grouping of existing and developing power transmission line inspection robots is given, and the studies in the literature about line suspended inspection robots are compiled and summarised in tables. The fourth section presents the challenges and feasibility of inspection robots. Results and evaluations are shown in the fourth section.

2 Control Systems

The goal of the inspection robots is to perform maintenance and inspection tasks automatically; that is, the robot can overcome obstacles and roam freely on power lines. Inspection robots are moved along transmission lines using various control methods. Different motion sequences are designed for robots with the control methods used. The Expliner is semi-automatically controlled by a wireless system with two omnidirectional antennas on the robot and one directional antenna on the control unit. [11, 34]. In later studies, modes such as Line Loading Mode, Obstacle Navigation Mode, and Slope Mode were developed, and various attitude controls of the Expliner robot were carried out [35]. For the robot suggested in [36], a remote control model and an autonomous control model have been developed, including autonomous motion for obstacle identification, motion planning, overcoming obstacles, etc., and autonomous inspection for the transmission line. The robot can plan real-time movement based on the environment and the robot's posture signals.

The result of the optimum motion decision is transferred to the robot's controllers and drives the relevant axis. Field [37] proposes an expert system based on knowledge and inference for robot control. First, the test line was numbered, and then the characteristics of the obstacles associated with it were extracted. The sensor information is compared with the information in the knowledge base, allowing the robot to act according to the highest priority rule provided. In reference [38], a two-level distributed expert system (DES) is proposed for robot control. This system simulates decision making, analysis and judgment processes. The tasks to be fulfilled are first separated and then grouped, taking into account the functions and movements of the robot. Thus, the two-level DES system works together and makes decisions to control the robot. In reference [39], a closed-loop controller based on adaptive fuzzy logic is designed to evaluate the signals from the cameras and sensors on the robot and perform the necessary procedures to overcome obstacles. This controller drives the motors in a closed loop to provide complete control of the robot by outputting the Direct Current (DC) motors on the motor with pulse-width-modulation (PWM) waveforms. An ARM (Acorn RISC Machine) chip executes the control algorithm, and an FPGA (Field-Programmable Gate Array) chip is used to process the sensor signals. In reference [40], a control mechanism with three levels is used: organisation level, coordination level, and executive level. In the control mechanism, there is a control station on the ground and a local control system on the robot, and the communication between these two is provided wirelessly by the Radio Frequency (RF) module. Macro instructions such as overcoming obstacles, climbing, and running along the line can be given at the ground control station. By separating these instructions into micro movements, such as adjusting the robot's posture, catching the line, etc., the robot automatically performs the necessary procedures for the inspection process.

3 Existing and Developing Power Transmission Line Inspection Robots

Existing and developing robotic technologies for overhead electric power transmission lines are divided into the following categories [16]:

- Line Suspended Robots
- Unmanned Aerial Vehicles (UAVs)
- Ground Based Robots
- Other types of robots (e.g., climbing robots and insulator robots)

In this study, only 'Line Suspended Robots' in the literature have been compiled. Line suspended robots are designed to serve as the extended eyes and arms of the transmission lineman. Their primary design function is to perform visual inspection in transmission lines that are located in challenging areas, such as large rivers or highlands. Such robots or moving platforms can travel over the live line or ground wire of transmission lines, and many of them can pass through or cross over different obstacles [16].

Inspection robots have been distinguished as an alternative method to traditional inspection methods in checking power transmission lines. Robots usually move on transmission lines with the help of pulleys and hang on transmission lines. Robots generally have cameras for visual and thermal inspection, power supplies, motors for motion, a current transformer for measuring transmission line current, a voltage transformer for measuring transmission line voltage and communication, and control unit for remote robot control, and various sensors. In addition, robot bodies usually consist of lightweight material (aluminium, carbon fibre, etc.) [5, 31]. In the last thirty years, power transmission line inspection robots have been the focus of many scientists and research centres in many countries. Various developments and transformations have been recorded in this regard. Today, inspection robots continue to be developed to monitor and inspect power transmission lines and components economically, safely, and quickly without power interruption and any problems. While some of the inspection robots are commercialised [41–43], the development and prototype trials of some continue. In this study, power transmission line suspended inspection robots in the literature are grouped as robots that can move on live lines and ground wire. Robots moving on the live line are grouped as robots moving on multiple wires and a single wires. Some of the robots discussed in this paper are presented as designs (Computer Aided Design (CAD) models) only, not yet in the prototype stage.

3.1 Robots Moving on Live Line

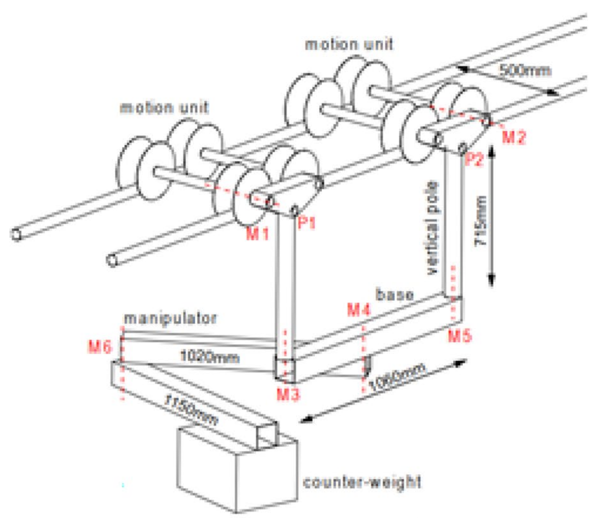
In recent years, in studies on power transmission line suspended inspection robots, robots moving on a live transmission line have been proposed and designed to examine the transmission line in detail. These robots are discussed below by grouping them as robots moving on multiple wires and single wires. Some inspection robots presented here that move on multiple wires can also move on single wires during obstacle crossing.

3.1.1 Robots Moving on Multiple Wires

In reference [11], the development of a remote-controlled robot called Expliner, designed for line inspection of high voltage transmission lines, is presented. The robot is designed to overcome suspension clamps, cable splitters, and other obstacles that prevent robots from inspecting transmission lines. The robot has two support points (robot arms) and a counterweight (base structure) (Fig. 3). DC motors are utilised to provide the electrical drive of the robot arms. By adjusting the position of the counterweight, the centre of mass can be altered, allowing for the removal of one support point. In addition, a manipulator, control system, and portable control unit provide wireless control.

Several aspects have been noted that further development is required for the robot. These include the mechanism to enable continuous movement and obstacle avoidance on inclined cables, weight reduction by resizing the actuators, prevention of control loss in situations such as strong winds, and mitigation of the effects of the electromagnetic field to ensure the robot's operability on 500 kV transmission lines.

In reference [36], an autonomous inspection robot prototype is explicitly developed for bundle conductors ranging from 220 to 500 kV. Designed for the bundled conductor shown in Fig. 4, the robot can move on the 220 kV twin-bundle conductor and four-bundle conductors. It can perform inspection by overcoming all kinds of obstacles. The robot's capability is demonstrated through an examination conducted on a 220 kV twin-bundle conductor using the prototype. Figure 4a shows the robot controlled for a



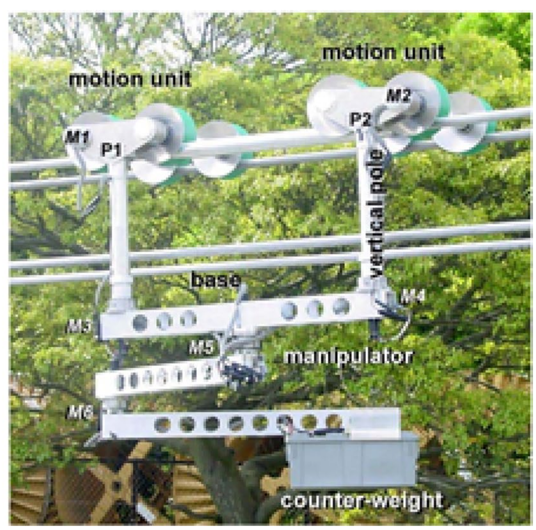


Fig. 3 Expliner prototype and subcomponents [11]

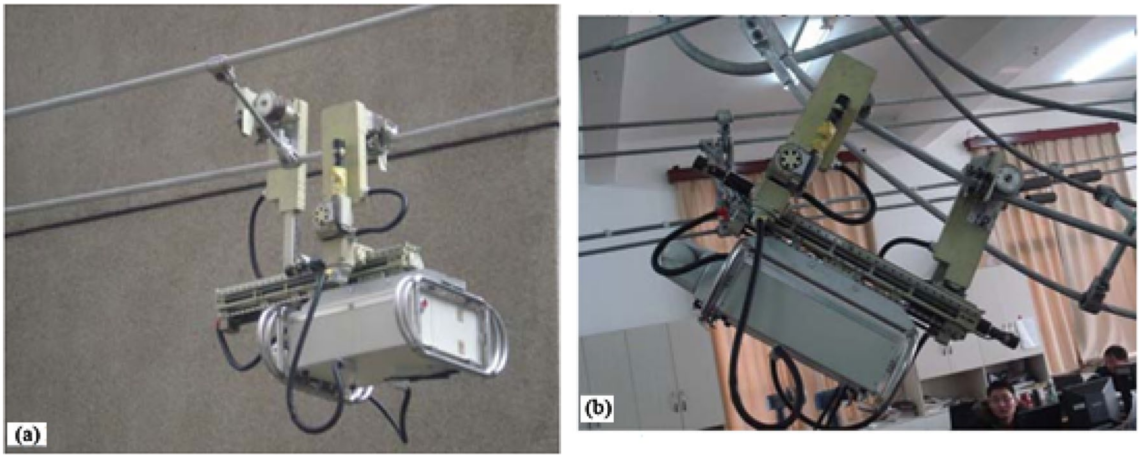


Fig. 4 **a** Motion in twin bundle conductors **b** motion in quad bundle conductors [36]

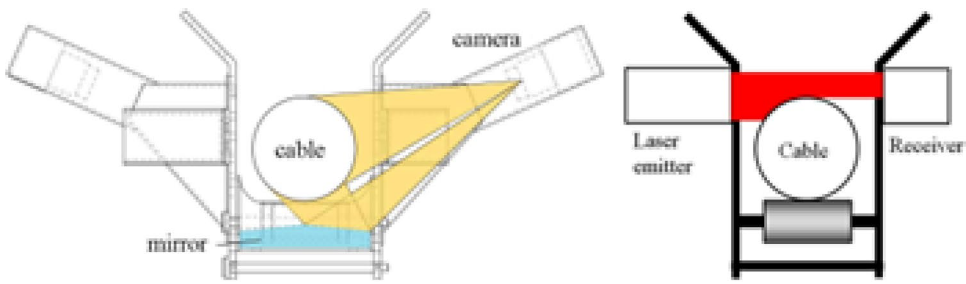


Fig. 5 Transmission line imaging (right) and principles of diameter measurement (left) [34]

twin-bundle conductor, and Fig. 4b for a quad-bundle conductor. The obstacle overcome and adjustment mechanism of the mobile robot is designed as a combined mechanism with two asymmetrically distributed forearms, an expandable rear arm shared by the two forearms, and a centre of gravity adjustment device. Researchers stated that studies on joint automatic control, multi-sensor detection data, and machine vision are ongoing.

In reference [34], the Expliner has been further developed to increase the safety and manoeuvrability of the robot during inspection operations. Charge Coupled Device (CCD) cameras and mirror assembly have been designed to monitor the deformations and corrosion in the transmission lines (Fig. 5). Laser sensors have been added to measure the diameter of cables. The measuring principle is shown in Fig. 5 and consists of a laser transmitter and a receiver with a cable between them. In addition, safety hooks have been added, and the number of wheels on each arm has been reduced to two (Fig. 6).

In reference [35], several improvements have been made to enhance certain features of the Expliner robot (Fig. 7). These improvements are as follows:

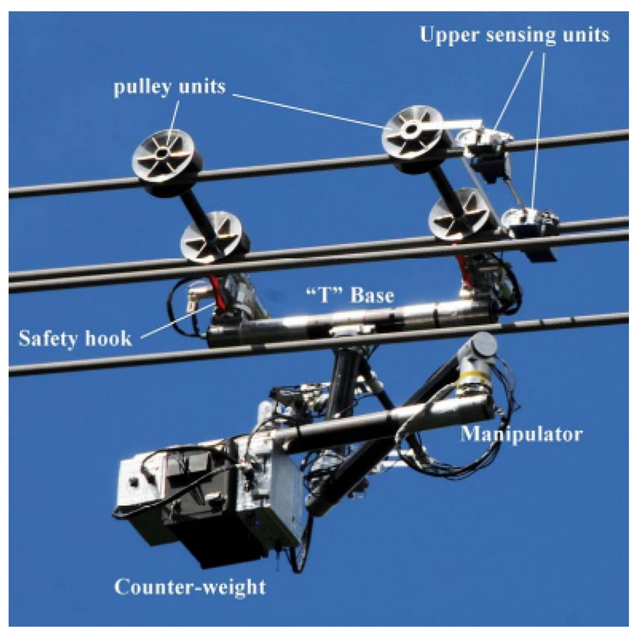


Fig. 6 Expliner and its main components [34]

a. Two sets of drive pulley shafts have been implemented to drive the robot. The short set, equipped with only one drive pulley, is specifically designed for single cable

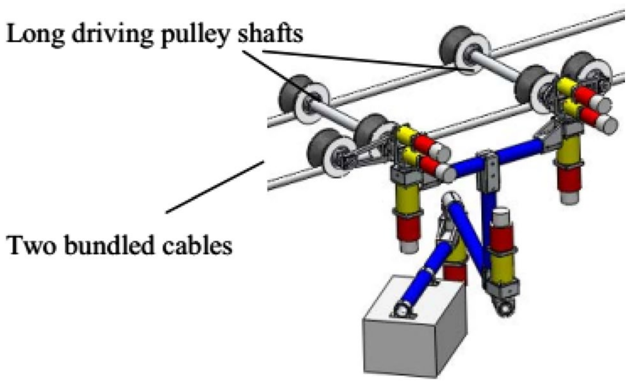


Fig. 7 Expliner robot with improved arm mechanisms [35]

scenarios. On the other hand, the extended set, featuring two drive pulleys, is dedicated to situations involving two or four bundled cables.

b. Two auxiliary arms that can rotate around their corresponding drive pulley shafts have been added to improve obstacle overcoming capabilities and enable operation on highly curved cables. This design ensures that the robot always maintains at least two suspension points on the cable, resulting in improved reliability and accuracy of motion control.

The driven pulleys mounted on the auxiliary arm placed under the cable can be used as pressure pulleys that allow the robot to climb up inclined cables with less risk of slipping and falling. In addition, the tilt angle and movement speed have been increased.

In reference [44], the Inspection and Foreign Object Removal Robot (IFBRR) for power transmission line inspection is introduced. This robot is designed to walk smoothly on the transmission line and overcome the obstacles on the line. The structure of the robot is shown in Fig. 8. The robot consists of a body mechanism, tensioner mechanism, foreign body scavenging mechanism, and drive wheel mechanism. The robot uses four drive wheels to move on the twin bundle transmission line and is pressed onto the line by two tensioning agents. When the robot approaches foreign objects, it halts its swinging cutting arm to remove the foreign object. The results of the robot motion simulation indicate that the asymmetrical drive wheel, resembling a "V" shape, performs better than the symmetrical drive wheel when the robot moves on a spacer. Furthermore, it is mentioned that this robot is lighter in weight than other robots in the literature.

To advance the goal of comprehensive inspection of the electrical grid, Hydro-Québec, a company, has developed an innovative and user-friendly robot called LineRanger [45, 46]. The LineRanger robot is created following the field deployment of LineROVer and LineScout. The robot named LineROVer mentioned here was introduced in 2000 as an overhead ground wire deicing application [47, 48]. The robot named LineScout was presented in 2008 as an inspection robot that can roll either on a single live conductor or one of the bottom conductors of a bundled configuration [49]. LineRanger (Fig. 9) includes high safety and efficiency, high quality vision control, high speed, and high-level approaches to obstacle avoidance. The robot is designed with four arms connected to

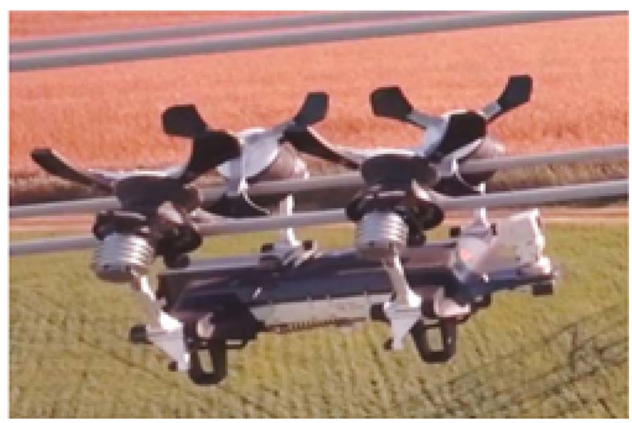


Fig. 9 LineRanger prototype [45, 46]

Fig. 8 General structure of the robot [44]

the robot base via springs. It rolls on four wheels along the two lower conductors of a bundle. During the obstacle crossing function, the arms passively open, and the wheels roll over the obstacle. The paper highlights that LineRanger is considered the most advanced climbing and inspection robot developed to date.

The summary information of the inspection robots that can move on multiple wires the compiled is shown in Table 1.

3.1.2 Robots Moving on Single Wires

In reference [38], a transmission line inspection robot based on expert system methods is presented, and a new control strategy and real-time implementation are proposed. The robot consists of five parts: palm clamp on–off device, flexible arms, a drive mechanism, brake system assembly, a controller, and power supply. The mechanical structure of the robot with 16 axis motion is shown in Fig. 10. The drive wheels are flexibly attached to the body and have a hollow structure that allows the robot to overcome obstacles easily. This hollow frame structure

Table 1 Robots moving on multiple wires

	Robot	Publication year	Description*	Weight	Figure	References
1	HiBot company, Japan (Expliner)	2008	The robot has two support points (robot arms) and a counterweight (base structure). It has 8 active wheels	84 kg	Fig. 3	[11]
2	Wuhan university, China	2010	The robot, which can move on the bundle conductor, consists of two asymmetrical arms, the expandable rear arm connected to these arms and the centre of gravity adjustment mechanism. The robot charges the batteries by taking advantage of the magnetic field in the transmission line	*NP	Fig. 4	[36]
3	HiBot company, Japan (Expliner)	2010	It is an improved version of the Expliner robot. Cameras and mirror assembly, laser sensor, safety hooks have been added. There are 4 active wheels	*NP	Fig. 6	[34]
4	Sichuan university, China (Modified expliner)	2012	The arm mechanisms of the Expliner robot are modified. Thanks to the additions made, the robot can move both on a multi-conductor and a single conductor. It has 6 active wheels	*NP	Fig. 7	[35]
5	Xi'an Jiaotong university, China	2018	The robot is designed with power transmission line inspection and foreign body removal (sweeping) tasks. The body mechanism is at the top and there are 4 asymmetrical wheels	*NP	Fig. 8	[44]
6	Hydro-Québec company, Canada (LineRanger)	2019	The robot has 4 arms that are connected to the robot base by springs. The robot rolls on four wheels along the two lower conductors of a bundle. The prototype weight is approximately 45 kg	45 kg	Fig. 9	[45, 46]

*In some studies, information about the weight, arm structure and other parameters of the robots are not provided (NP)

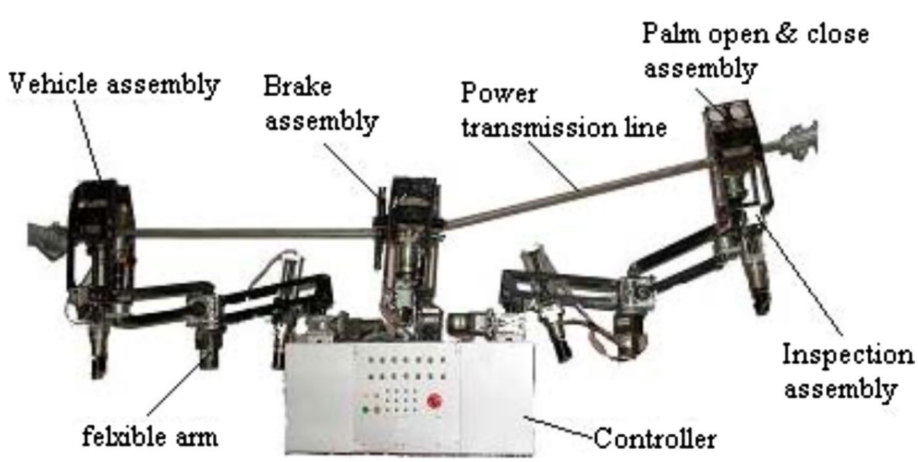


Fig. 10 Inspection robot configuration [38]

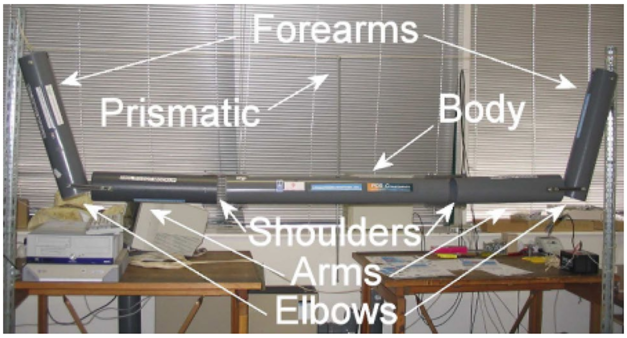


Fig. 11 RIOL robot model [50]

has been effective in increasing the robot speed. Flexible arms are created with a cascade connection that provides a constant angle and level for the palm when the long and short arms are turned up and down. This structure provides the advantage that joint controllers are much simpler. The tests performed in the laboratory environment were successful and promising. The project continues to develop the mechanical structure and control algorithms of the system for industrial environment tests.

Studies in [50, 51] describe ongoing studies of a transmission line robot prototype capable of monitoring/surveillance (inspection) along transmission lines. The robot, called RIOL, has a central body and three serial arms on the body (Fig. 11). The body consists of three blocks connected by vertical rotation joints that allow the robot to move between lines in different directions and control its centre of mass. Two of the arms allow the robot to move using the brachiation movement, while the third arm in the middle provides balance. In addition, this third arm helps the robot pass through obstacles and helps to keep the torques required by the other arms at reasonable values. DC motors are utilised to drive the robot arm and joints. The articles present key simulation results and details of the prototype under development. Pre-simulation results showed that off-the-shelf actuators can be used in real prototypes. It has been stated that the work for the flexibility tests for the robot, the design of the claw brake mechanism and the production of life-size prototypes is ongoing.

In reference [12], a brand new mechanical structure is designed for the inspection robot and all its parts, and the mechanical structure is fully explained. A robot prototype is developed consisting of five arms, two prismatic hanging arms at the front and rear, and three arms with wheels rolling along the line in the middle (Fig. 12). DC motors are utilised to perform robot movements. These motors are driven by H-bridge module LMD18200T and Silicon Lab Corporation's high-performance single-chip C8051F047. When the robot prototype was completed, the experiment was carried out on the simulation line. The experimental result has shown that this robot performs tasks such as obstacle crossing, and long-distance wire tracking and works stably.

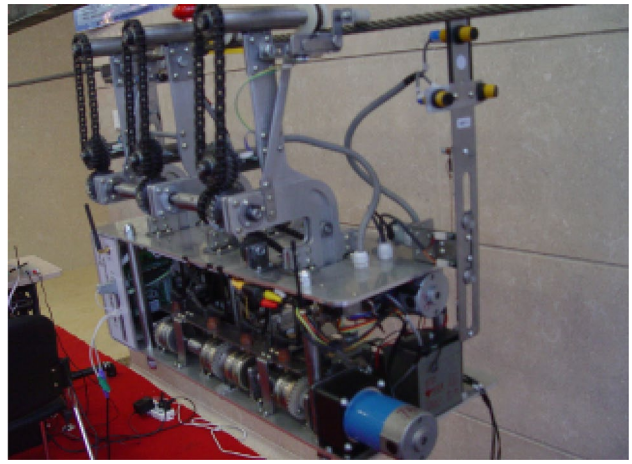


Fig. 12 Robot prototype [12]

The robot named HQ LineROVer, manufactured by the Hydro-Québec company was first presented as a ground wire defrosting application at the ESMO conference in 2000 [47, 48]. The prototype has since grown into a third generation Remote Controlled Vehicle (ROV) called LineScout [49, 52–55].

LineScout's mobile platform is designed as a two-wheeled vehicle to optimize energy efficiency by travelling along unobstructed sections of power lines [52]. Two brushless DC motors, DIS1 and DIS2 in Fig. 13a, provide LineScout motion. Thanks to a pair of safety rollers driven by ROL1 and ROL2 mounted next to the wheels, and the robot is fixed on the line while standing next to the obstacle to be crossed. In addition, the robot includes modules such as grippers (GRP1-2), electromagnetic brakes (ARM1-2) and cameras (CAM1-2–3). LineScout's mobile platform is shown in Fig. 13b.

The third-generation prototype has been tested and validated under field conditions [49]. In the study conducted in 2012 [55], field-based test results collected in the last two years are presented.

An autonomous inspection robot prototype for 220 kV single-phase line is presented in reference [36], (Fig. 14). The robot is designed in such a way that it can move independently along the single line and overcome various obstacles (such as shock absorbers, suspension clamps, tension clamps). Thanks to its five joints, the robot can perform tasks such as moving along the line, crawling along the jump line, rolling along the unobstructed section, and overcoming combined obstacles. The robot comprises electromagnetic shielding, control, inspection, communication, and navigation systems. Robot control is carried out by communicating with the base station on the ground. It consists of base

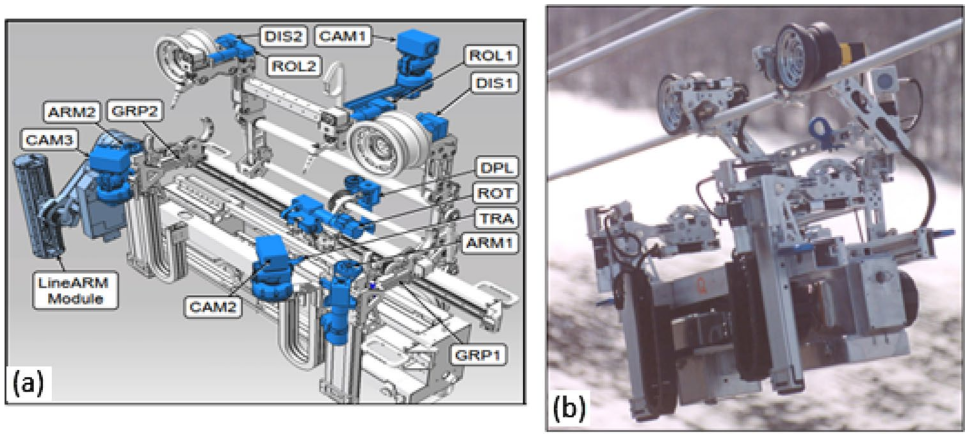


Fig. 13 **a** Linescout components, [52] **b** Linescout prototype [53]

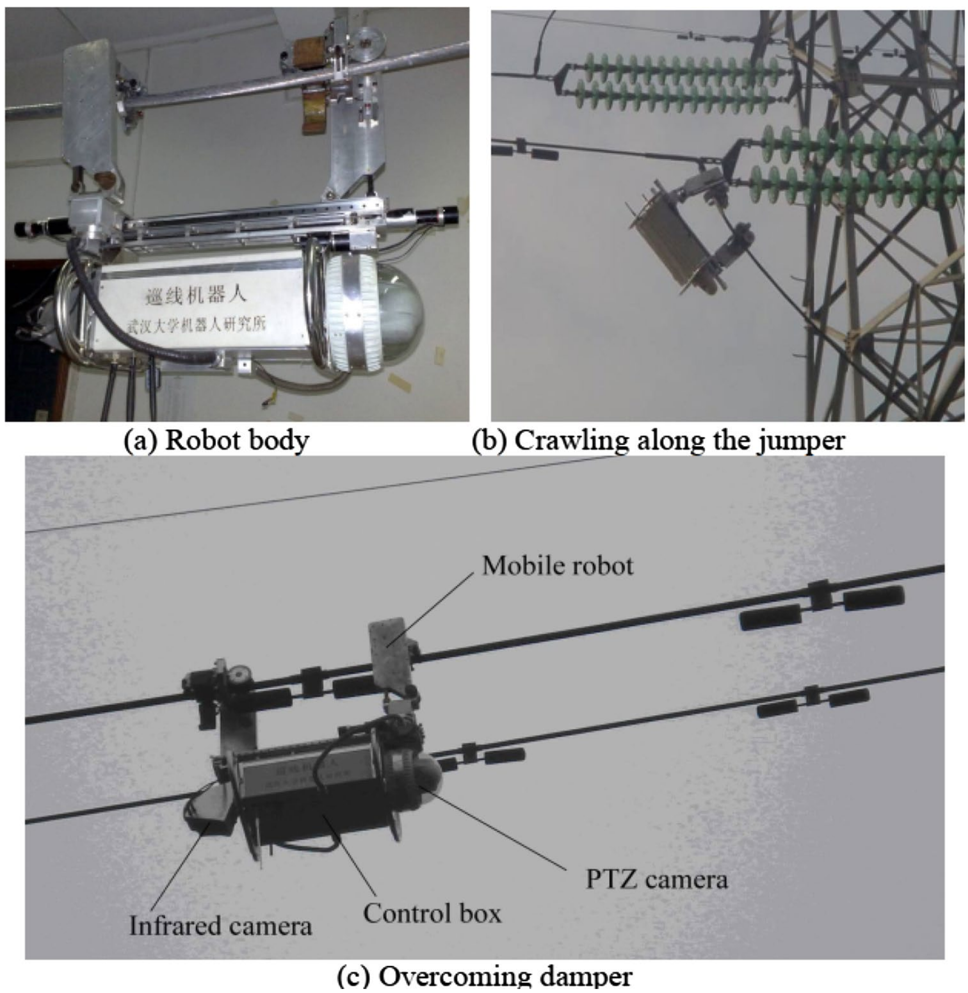


Fig. 14 Inspection robot and field application test for 220 kV single line [36]

station, power system, image capture card, wireless data transmitter, image wireless transmitter, and workstation. Field studies of the robot are carried out and its functions and technical parameters are verified.

In the studies presented in references [17, 37, 56], the mechanical structure and control system of a new type of crawler power transmission line inspection robot is presented (Fig. 15). The new kind of robot has three arms connected to each other via a base and a balance mechanism. Also, the control strategy of the robot is integrated with artificial intelligence and proposed with a rule-based expert system for optimal decision making. The inspection robot can operate

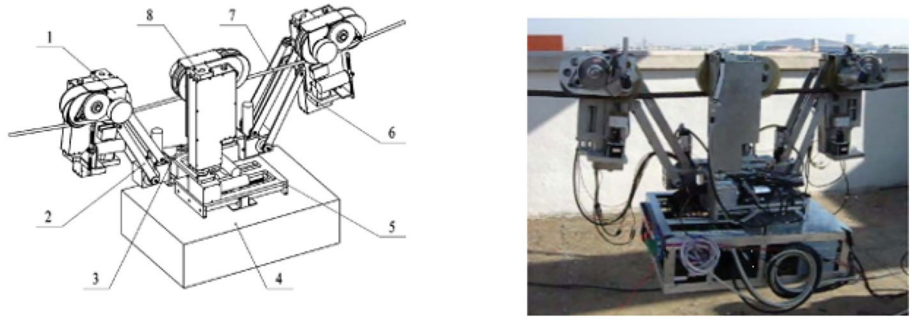


Fig. 15 Schematic of robot structure (left) and robot prototype (right) [17]

Fig. 16 Inspection robot prototype [39]

autonomously along lines and automatically cross various obstacles along real lines. As a result of laboratory tests of the prototype, it has been observed that it has successfully overcome many types of obstacles.

In reference [39], a robot is designed to inspection high-voltage power transmission lines by imitating the movements of monkeys (Fig. 16). In the paper, the framework, modelling, controller design, simulation and experimental results of this two-armed inspection robot are presented. The inspection robot has a mechanical design with a bionic structure. The robot has two multi-jointed arms with claws and a wheel on each arm. The counterweight box is designed to adjust the centre of gravity (COM). The robot can be driven along the line when there are no obstacles with its wheels. It can turn around and overcome an obstacle when it encounters it. DC motors utilised to perform robot movements are driven by closed loop with the help of an ARM chip and FPGA chip.

In references [57–62], a mobile mechanism with bipod configuration is proposed to inspect the power transmission line (Fig. 17). The wire-walking function of the designed robot mechanism consists of a single support phase and a double support phase. In the single support phase, while one-foot hangs on the line, the other foot swings back and forth, overcoming the obstacles on the line and performing

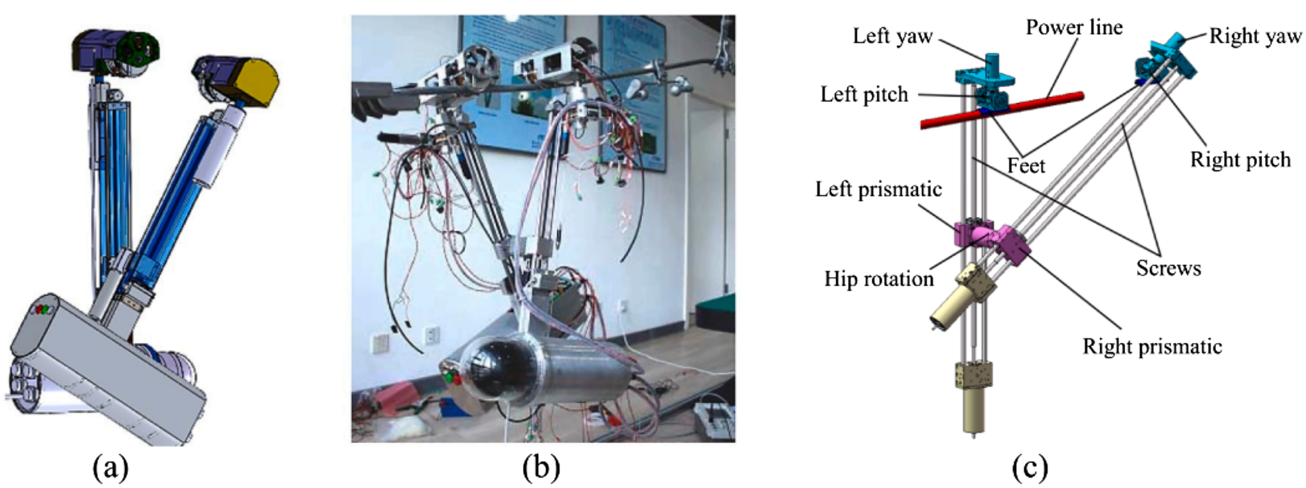


Fig. 17 **a** Line walking design **b** Test mechanism on power transmission line [60, 61] **c** Static walking structure [59]

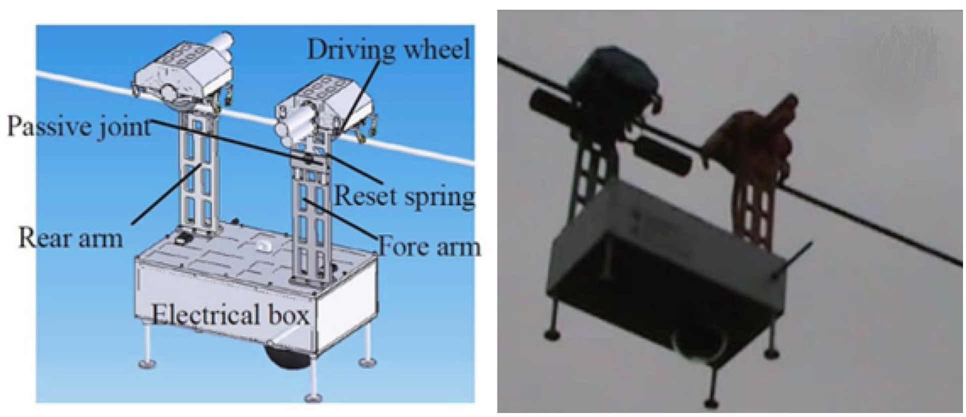
the wire walking motion. The parts of the robot that make rotational movements are driven by DC motors, and DC servo motors drive the parts that make prismatic movements. A closed box is placed on each leg, which acts as a counterweight. The boxes house the battery, the controller, and the sensing and display unit. While most transmission line inspection robots turn using their wheels, this robot walks along the line, raising one foot at a time (static walking).

In reference [63], a new inspection robot with passive joints (Fig. 18) is presented with its quasi-static model set up for obstacle-overcoming analysis. A new wheel-arm hybrid control mechanism is proposed by adding a passive rotary joint to each arm of the two-arm robot. The inspection robot has been shown in an experiment on a 500 kV line where it can overcome obstacles such as vibration dampers and splice sleeves.

In reference [64], a mobile robot for high voltage power transmission line inspection, consisting of a three-coordinate swivel wheel machine and three suspension arms, is presented (Fig. 19). The robot's walking and hanging actions are driven by DC motors. In addition, a control method is designed for obstacle avoidance. An experiment has been made on the prototype robot, and it has been observed that it can overcome the obstacle. However, prototype figures are not presented in the article.

In reference [33], a robotic system is developed by The Electric Power Research Institute (EPRI) to provide autonomous control of overhead transmission lines (Fig. 20). This work describes this robot, which is also shown in the video presentation in reference [65]. In addition to determining the status of critical components in the transmission line, the robot is also intended to assess vegetation infringement and right-of-way (ROW) management issues. The robot can overcome through different obstacles without raising any of its arms. However, for the robot to overcome obstacles in this way requires that actual transmission lines be equipped/modified with custom-made railing systems (jumper or auxiliary bridge) around any given components. The robot can collect inspection data using onboard visual cameras, Radio Frequency Interference (RFI) detector, Global Positioning System (GPS), Light Detection and Ranging (LIDAR), weather sensor systems, and an infrared camera.

Fig. 18 Robot model and field experience [63]



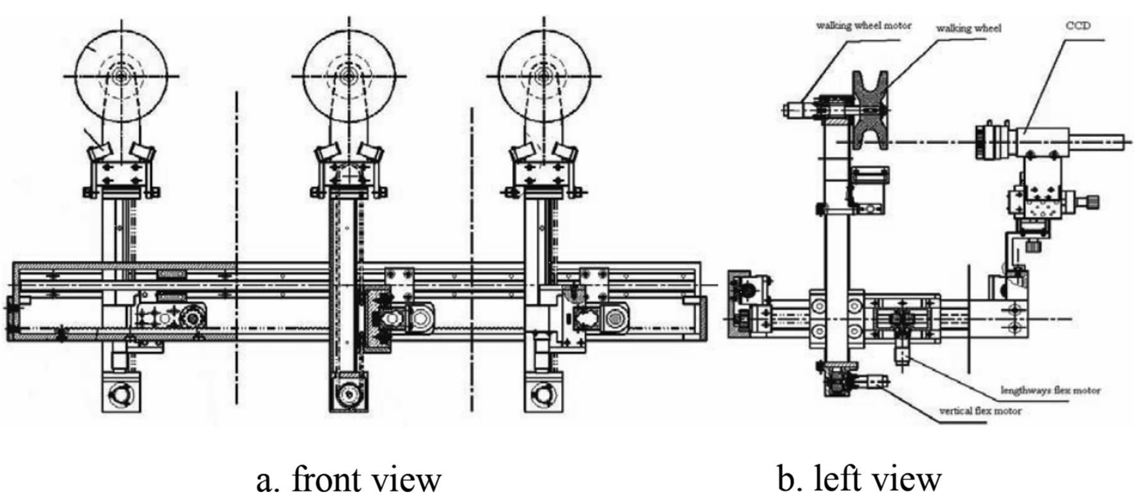
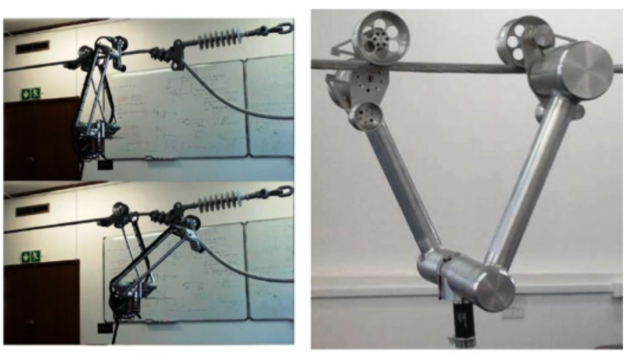


Fig. 19 Robot drawings [64]

Fig. 20 Robot prototype [65]



(a) (b)

Fig. 21 **a** Passing of the robot over the jumper **b** robot prototype [66]

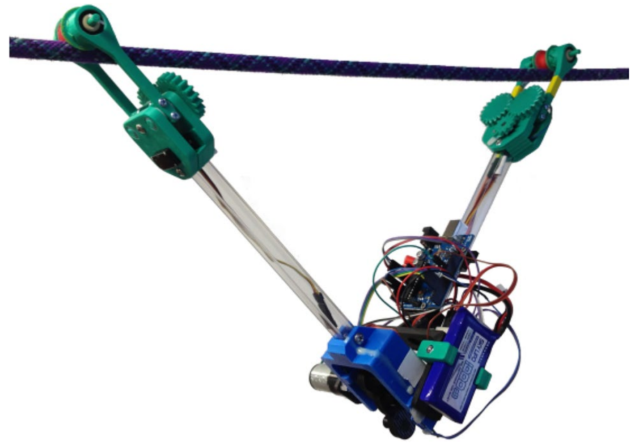


Fig. 22 SkySweeper prototype [68]

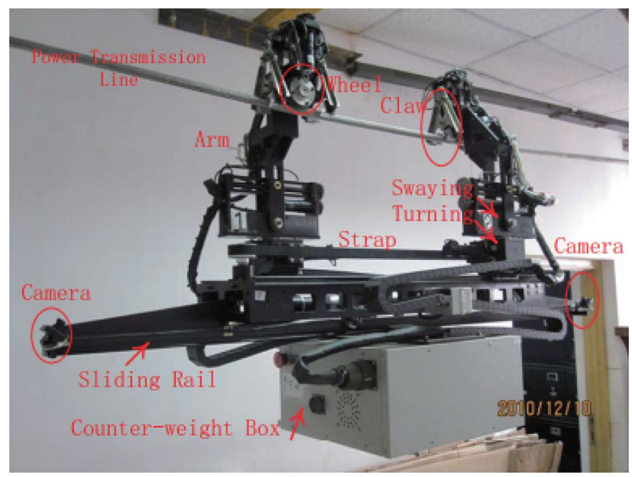


Fig. 23 Robot prototype [40]

Reference [66] presents an approach for specifying the number of degrees of freedom in a power line-mounted inspection robot that can climb around obstacles on overhead conductors, including jumpers (Fig. 21). Two prototypes are presented in the study and the second prototype is developed with the experience gained in the first prototype. The second prototype is presented as a triangular two-armed robot. Two pulleys are mounted at the ends of the arms, the smaller one is the passive pulley for support, and the larger one is the active pulley. Brushless DC motors are utilised for the driven of robot movements. The robot needs the jumper cable (or auxiliary bridge) to cross the obstacles. Manoeuvrability tests of the prototype two robot are shown in the video [67].

In reference [68], SkySweeper, a mobile robot that can rotate its whole body, designed to work in environments such as cables, wires, power lines, is presented (Fig. 22). The robot consists of two links axially connected at one end, a series of elastic actuators at this "elbow" joint can actuate the relative rotation between the two links. An actuated three-position clamp is located at the opposite end of each link. The clamp can be open, partially closed, or fully closed to enable various manoeuvres. Brushed DC servo motors are utilised to drive robot movements. During obstacle avoidance, one arm leaves the line and then turns 180° to overcome the obstacle. The test of the prototype robot is shown in the video [69].

In reference [40], an inspection robot with a symmetrical structure is presented to inspect high-voltage power transmission lines. The robot consists of two symmetrical arms with gripper wheels and the main body (Fig. 23). A counterweight box is placed at the bottom of the robot so that the COM of the robot body can adjust. The robot performs its inspection task by rolling along the transmission lines and overcoming the obstacles in the lines. A combination mode of teleoperation has been developed through the local intelligence and RF module based on the visual servo, and thus the robot control is realised. In addition, a visual servo-based controller has been developed so that the robot can fully grasp the transmission line. The effectiveness of the control method and the robot prototype has been proven due to the tests carried out in the laboratory environment.

In reference [70], the design of a low-cost and lightweight transmission line inspection robot called Robonwire is presented. The robot consists of three arms with two joints and a base frame (Fig. 24). The process of avoiding obstacles is carried out by rotating the robot's arms alternately laterally. Gears and wheels that will provide robot movements are driven by DC motors. In the study, the first stages of robot design are shared; in this process the robot can move on the wire. The authors stated that there is ongoing work on the obstacle avoidance process and adjusting the robot's centre of mass.

In reference [71], a three-armed robot is developed for power transmission lines inspection (Fig. 25). The robot arms have double parallelogram architecture (DPA). It is stated that this will provide benefits such as balancing the forces in the arms, increasing the movement efficiency of the arms in three-dimension (3D) space, and improving the ability to pass obstacles. Also, the centroid of the payload can shift over a wide range, reducing the motor load.

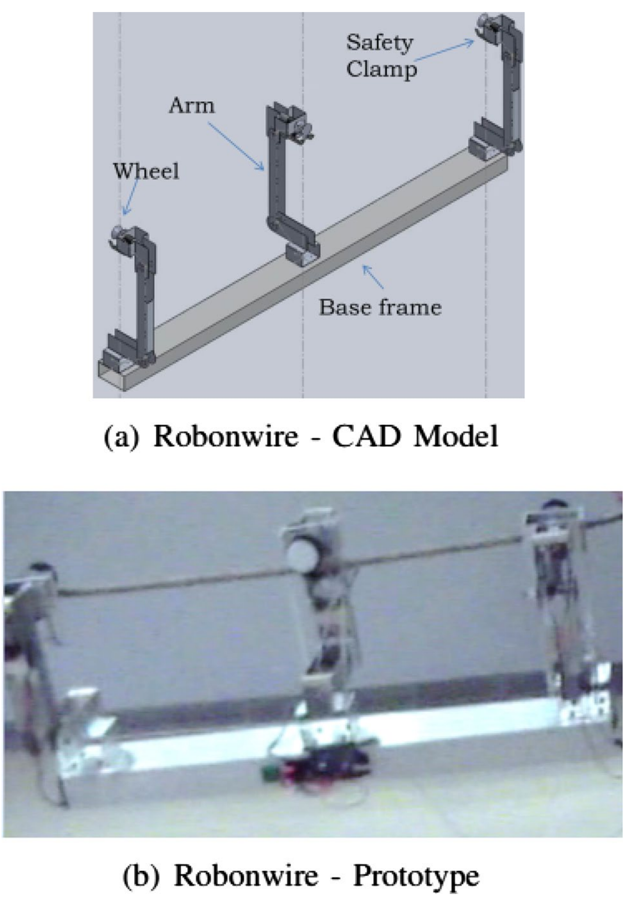


Fig. 24 Robonwire CAD model and prototype [70]

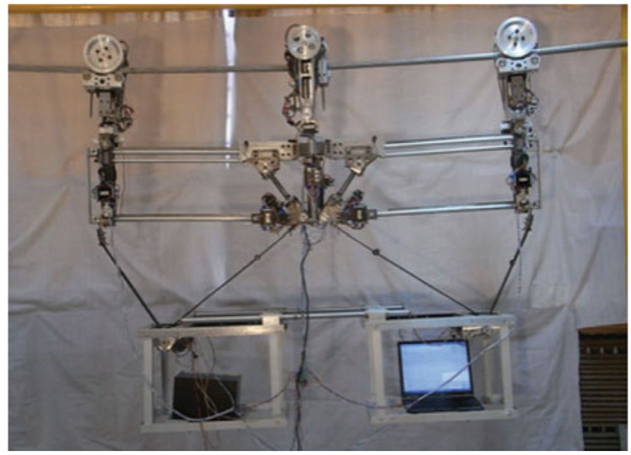


Fig. 25 Robot prorotype [71]

Experiments on the prototype robot confirmed the effectiveness of the designed mechanism.

In reference [72], an inspection robot is introduced as an alternative to the existing inspection methods of high-voltage power transmission lines. In the study, the mechanical structure and control system are explained. The robot consists of a suspension structure with three arms that can keep the robot suspended on the line and facilitate movement by reducing friction thanks to the wheels at its ends (Fig. 26). When the robot encounters the obstacle, the three arms leave the line one after the other, and again by holding the line, it performs the obstacle crossing process. Brushless DC motors drive the robot to perform the tasks of walking and spanning obstacles. In this study, only the 3D CAD model of the robot is presented. The simulation results showed that the robot motion performance and the control method used are successful.

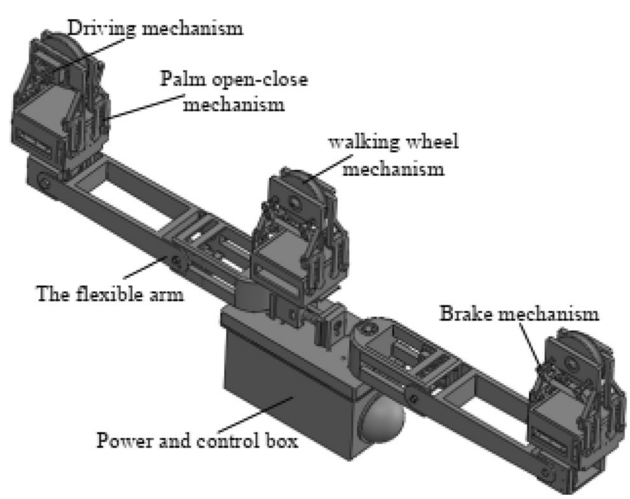


Fig. 26 Axonometric drawing of the robot [72]

Fig. 27 Robot prototype [73]

In reference [73], a new mobile inspection robot prototype is proposed to inspecting power transmission lines. The robot has three arms with rubber wheels at the ends (Fig. 27). At the ends of the two arms of the robot, there is a gripper mechanism designed to keep the robot stable on the line. Robot can roll over some obstacles (vibration dampers, compression splices, etc.) and clear some obstacles (suspension clamps, spacers, etc.). Since the longest of these obstacles are suspension clamps, the maximum obstacle length of the robot is designed as 350 mm. The authors stated that the robot has sufficient mobility to overcome obstacles but is still under development.

In references [74, 75], a mobile inspection robot is presented that can overcome different types of obstacles suspended on power transmission lines and/or telecommunication transmission lines. The robot has two pairs of identical legs, one in the front and the other in the back, and the legs on the same side have the same movement (Fig. 28). It can hang on the transmission line thanks to the hooks (feet) attached to each leg end. To change the leg length of the robot, stepper motors are driven, and to move the feet, DC motors are driven. The studies present the kinematic model of the mobile robot and the obstacle avoidance process. Graphical simulations and experimental tests are carried out, and it is stated that the effectiveness of the proposed system is proven.

Reference [76] presents a newly designed inspection robot and various methods for maintaining the stability of the robot while walking on the transmission line and overcoming obstacles on the line. The robot consists of two wheels and a swivel joint for each arm. The wheels are driven by DC motors (Fig. 29). The new dual-arm platform has 3 Degrees of Freedom (DoF)s from each component to perform rotate, lift, lower, and move in the direction of a wheel. To maintain the balance of the robot, a Fictitious Zero-Moment Point (FZMP) controller is used to ensure that the projection of the centre of gravity and the point of contact coincide. The performance of the methods used has been proven by experiments carried out on a real power transmission line indoors.

In reference [77], a new obstacle crossing mechanism is designed for the presented power transmission lines inspection robot. The proposed obstacle crossing mechanism includes lifting mechanisms, clamping mechanisms, drive mechanisms, and rotating mechanisms. The robot consists of two support arms, an auxiliary arm, and a control box (Fig. 30). The robot performs the functions of holding the transmission line firmly and climbing the sloped line thanks to the interaction of the clamping wheels and the driving wheels. Robot movements are driven by stepping motors

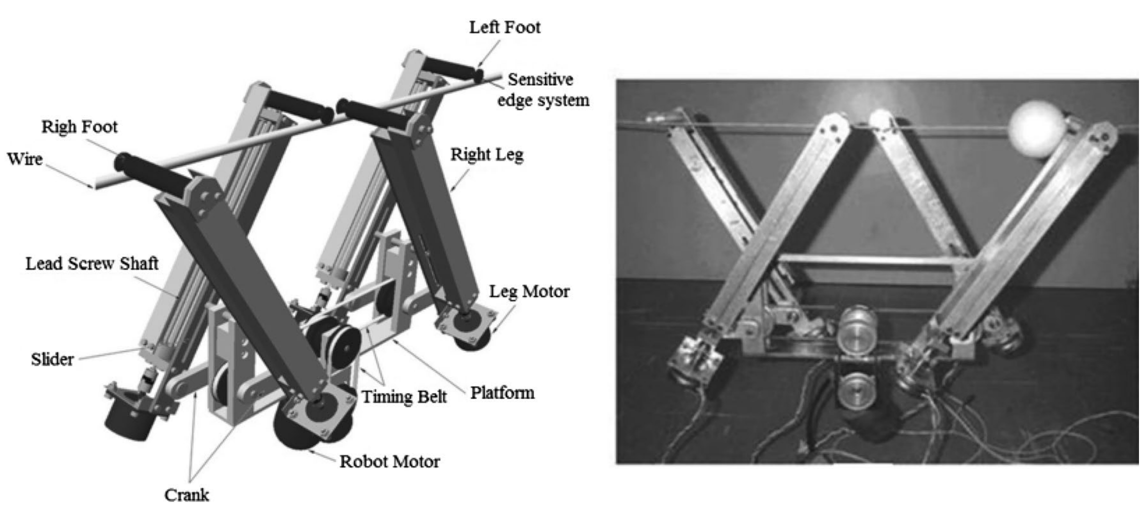


Fig. 28 General configuration of the mobile robot suspended on the cable and prototype [75]

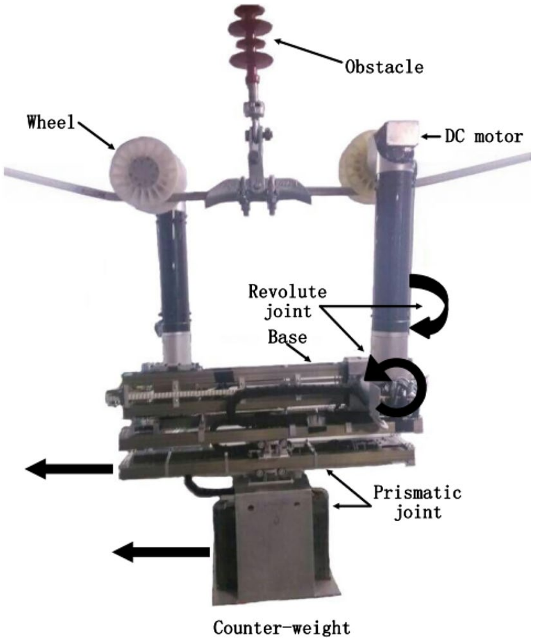


Fig. 29 General structure of the robot [76]

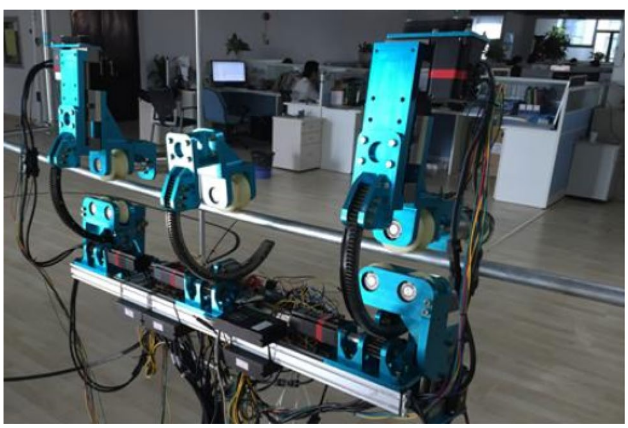


Fig. 30 Robot prototype on line [77]

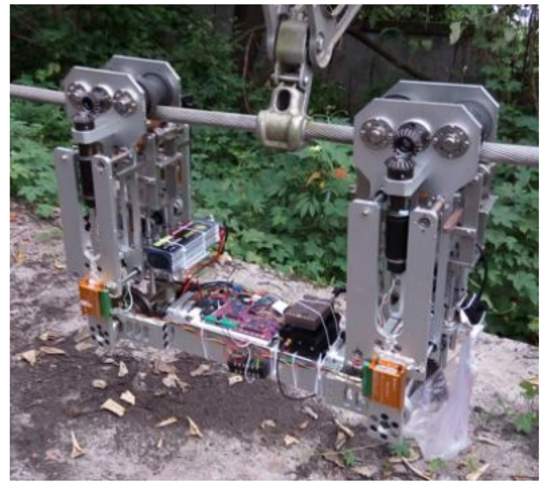


Fig. 31 Linebot obstacle crossing experiment [80]

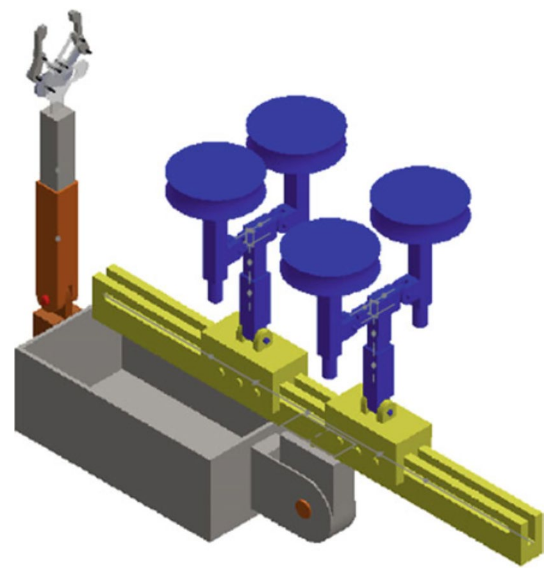


Fig. 32 Robot schematic [81]

and brushless DC motors. The prototype has been tested in the ADAMS (from MSC Software Corporation) simulation and on the established experimental platform. Experimental results and test results showed that the obstacle crossing mechanisms work with satisfactory performance.

In the studies [78–80], a four-armed robot named LineBot is presented (Fig. 31). The robot consists of a toothed joint, two gripping arms and two active arms. Linebot has 11 DoF in total. It is equipped with two open-closed wheels and a double gripper that can be driven separately. Brushless DC motors drive the movements of the active wheels of the robot. The pitch joint is placed in the middle of the Linebot to raise or lower half of the structure during obstacle overcoming. The robot has been tested on an unenergized power transmission line at a maximum tilt angle of 10°. The results showed that the robot has good mobility.

In reference [81], a new mechanical mechanism design is presented that provides dynamic stability, which is stated to provide more stable navigation than existing transmission line inspection robots. The proposed new mechanical design of the robot has three independent frames (Fig. 32): the wheel frame containing two pairs of motorised traction wheels (blue parts), an arm and a gripper arm frame (brown parts), and the centre frame (grey box). The grey box called the "main body" connects the first two frames, allowing them to slide and rotate. The behaviour of the inspection robot when crossing an obstacle is studied for four critical modes: (1) Moving on a cable with maximum slope of 30°

(2) Passing over aircraft warning lights, (3) Passing over aircraft clamps and dampers (4) Passing from strain insulators with/without twist in the horizon plane. It has been stated that the robot can overcome various obstacles, such as vibration dampers, clamps, warning balls on the wires. However, only the 3D CAD model of the robot is presented in this study.

The work in references [82, 83] presents a new bionic robot mechanism based on mimicking humans climbing trees (Fig. 33a) to overcome challenges in climbing performance and manoeuvrability for existing inspection robots. The robot is a new remote-controlled mobile robot for 500 kV power transmission lines and consists of two traction arms, two master arms and an electrical control cabinet. Servo motors drive robot arms and wheels. In the articles, only the dynamic model of the robot and the mechanism design (CAD model) are presented (Fig. 33b).

In reference [84], the movement of POLIBOT (Power Lines Inspection roBOT), a low-cost and low-weight transmission line inspection robot, is described. POLIBOT is a lightweight and autonomous operating solution for visual and thermal inspection of 138 kV and 500 A transmission lines. The robot consists of three modules or units: arm, traction, and support (Fig. 34b). Dynamixel MX-106R servo motors drive the traction system. CAD drawings of the robot are also shown in Fig. 34a. The robot design is inspired by the motion of the worm. The robot moves under the suspension cable using a series of claws in the same way as a worm.

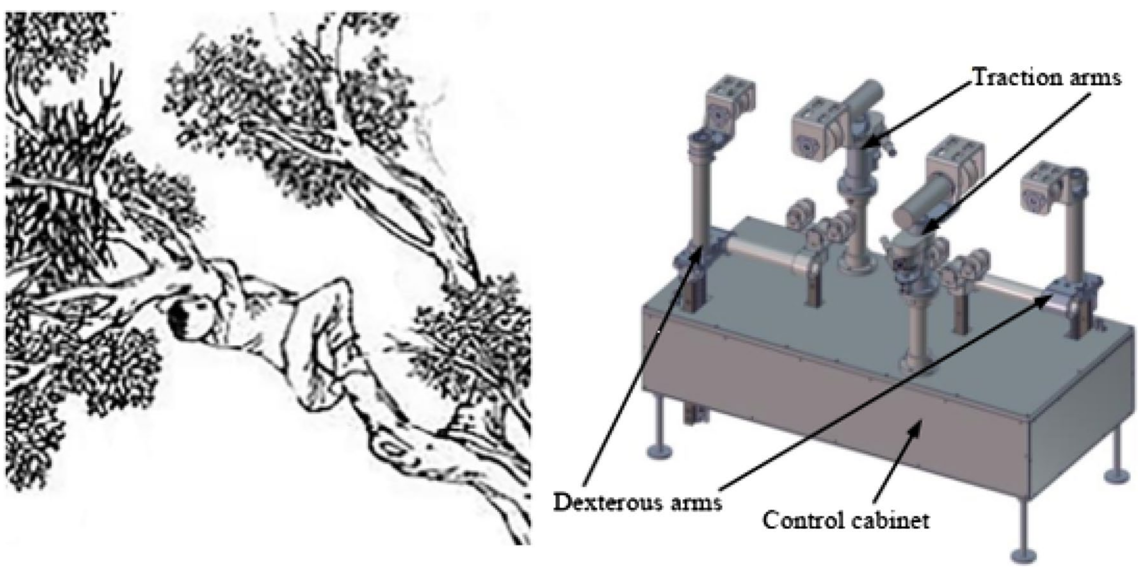


Fig. 33 **a** The act of climbing a tree **b** 3D robot model [82]

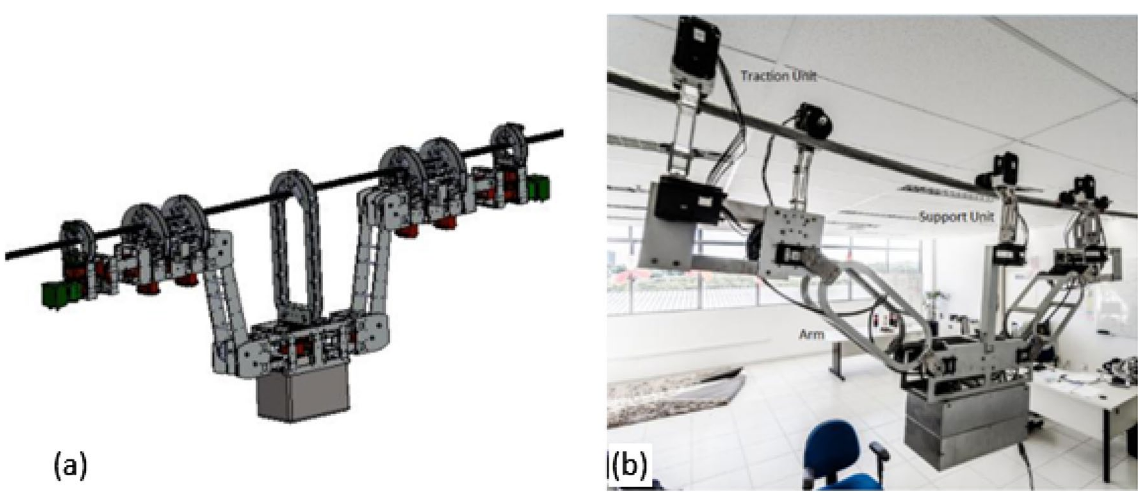


Fig. 34 **a** PILOBOT mechanical construction, **b** PILOBOT simple construction [84]

Also, the symmetry of the mechanism allows displacement of the suspension cable in both directions, eliminating the need to disconnect when the direction of control is changed.

Reference [85] presents a two-armed swinging power transmission line inspection robot by observing the motions of gibbons and combining these motions with the bionic principle. According to the gibbon model, the mechanical structure of the robot consists of three modules: shoulder, claw, and moving module. Figure 35 shows the general scheme of the robot. An unsymmetrical design is adopted to ensure the stability of the whole structure. Thus, it is ensured that the centre of gravity can be brought to the centre position during the operation. While the robot moves horizontally on the line, it can provide the same load distribution on the arm. However, only the 3D CAD model of the robot is presented in this study.

Reference [86] presents mechanical design of a low-cost, lightweight, compact inspection robot. The robot (Fig. 36) performs the functions of crossing and avoiding obstacles in transmission lines thanks to its robotic arm and pulley mechanism. The robot comprises 3 subsystems: roller mechanism, movable base and two components with 10 DoF. The movable base helps the robot move over the transmission line, and the pulley mechanism and 10 DoF double arms are subsystems that help overcome obstacles and towers. The robot is driven by DC motors for engaging and disengaging from the line, moving forward and backwards, and servo motors for locking and unlocking the support wheels. The robot has been tested on a transmission line installed for the experiment.

In reference [87], a two-link brachiation robot system that can walk on the line is proposed for the inspection of high-voltage overhead lines. The robot system has two gripping mechanisms and a body. The mechanical body of the bionic robot consists of two parts: a movable shoulder joint and two immobile arms (forearm and rear arm). These

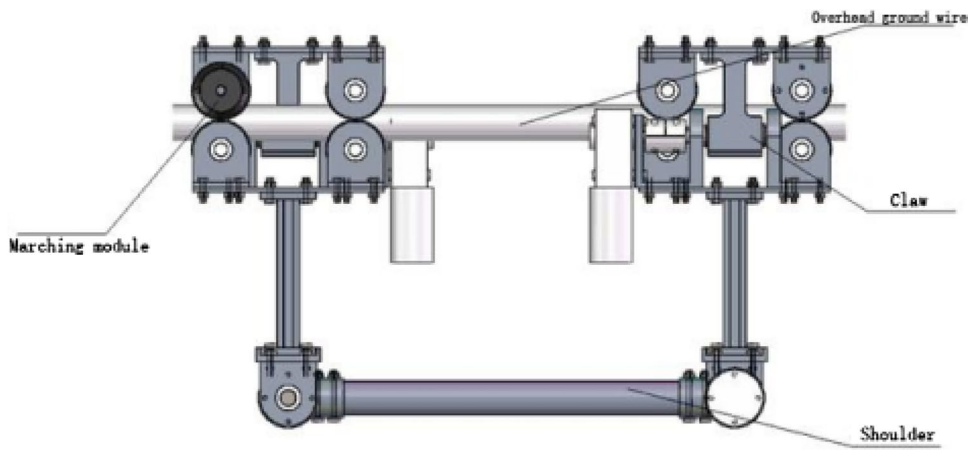
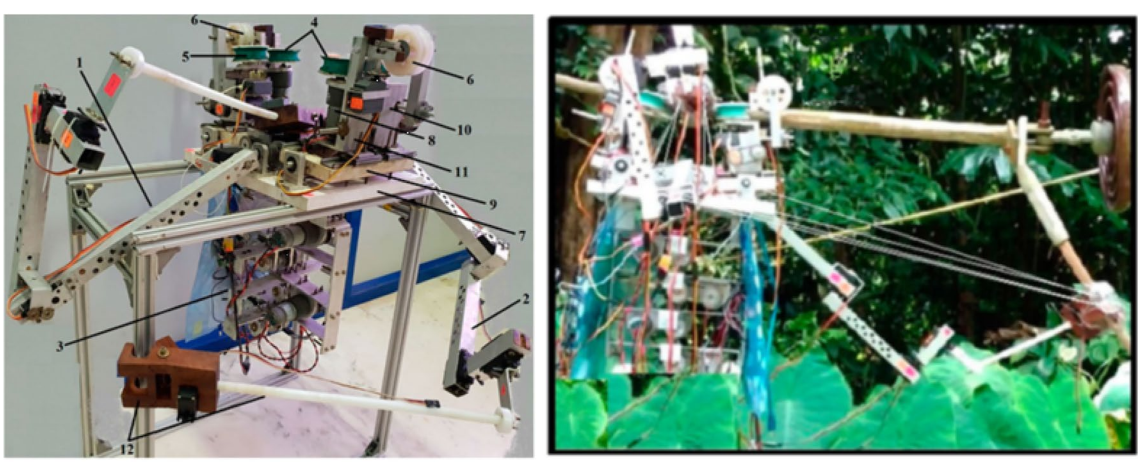


Fig. 35 Robot general diagram [85]



1.Arm1, 2.Arm2, 3.Pulley system, 4.Driving wheels, 5.Idle wheels, 6.Supporting wheels, 7.Robot base chassis, 8. Driving motor, 9.Pitch plate/swing unit, 10.Motor mount A (Retracting part A), 11.Motor mount B (Retracting part B), 12.Nylon rod and gripper hook.

Fig. 36 Robot prototype and tests [86]

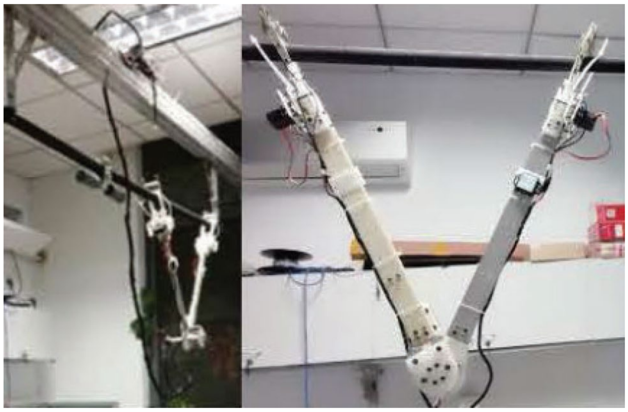


Fig. 37 Robot prototype [87]

arms are the same and connected to the lines with terminals. The robot prototype is as shown in Fig. 37. In the study, an energy-based controller is presented for tracking, obstacle navigation, stabilising obstacle crossings and online inspection tasks. The simulation results showed that the proposed control design can successfully guide the brachiation bionic robot to the required movements.

In reference [88], a low-cost, single-wheel drive mobile inspection robot named ROSETLineBot, which can move on power transmission lines, is designed. The robot mechanism consists of the main frame, actuator wheel, dummy wheel, and control box (Fig. 38). Thanks to the modular structure, different types of sensors can be easily integrated into the robot. SOLIDWORKS software is used to design ROSETLineBot during the prototype phase, and polylactic acid (PLA) filament is used for 3D printing of the robot. Each part of the robot is printed separately and joined with special fasteners. During obstacle crossing, the spring between the wheels opens as the actuator wheel tries to overcome the obstacle. Robot actuator wheels are driven by DC motor. With the expansion of the steel spring in the vertical axis, the robot gains the appropriate grip area and overcomes the obstacle. The prototype has been tested in a laboratory environment.

In reference [89], an inspection robot design with a mechanical arm that can be opened and closed symmetrically is presented. To control the robot's tracking movements, electromagnetic sensors are used to detect the distance to the obstacle. The robot consists of two crawling wheels, two clamping mechanisms, a ball screw, two crawling arms, stepping mechanism, a worm gear drive mechanism, stepping motor, etc. (Fig. 39). When the electromagnetic sensor detects the obstacle, the left and right half of the front crawler arm are removed symmetrically by the double-acting ball screw, then the front drive wheel is separated from the transmission lines. And the clamping mechanism is moved downwards to separate the transmission lines. Robot motion and obstacle crossing are modelled using the normal isometric curve of the equation of the lines. The accuracy of the model has been numerically verified with the example of 220 kV power transmission lines. The robot prototype can overcome obstacles on transmission lines and stably walk on power transmission lines.

In reference [90], a design diagram of the overhead transmission line inspection robot is presented. The goal is to solve the problems of low obstacle crossing efficiency and overhead fall prevention. A three-arm structure is adopted, as shown in Fig. 40. The front and rear arms are designed to roll forward. The middle arm moves forward and backward to adjust the robot's centre of gravity, allowing the robot to grasp the line. In addition, the palm grip structure is designed on the front and rear arms. Thus, the robot can easily overcome obstacles. However, a corner tower crossing

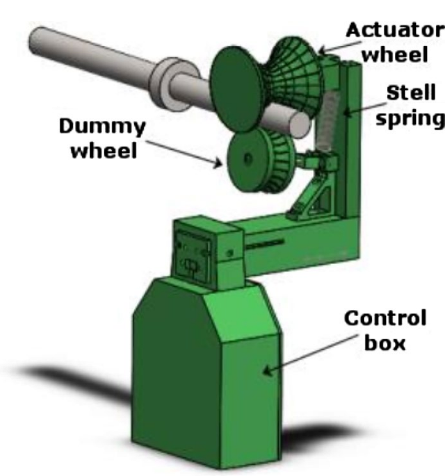


Fig. 38 3D model of ROSETLineBot [88]

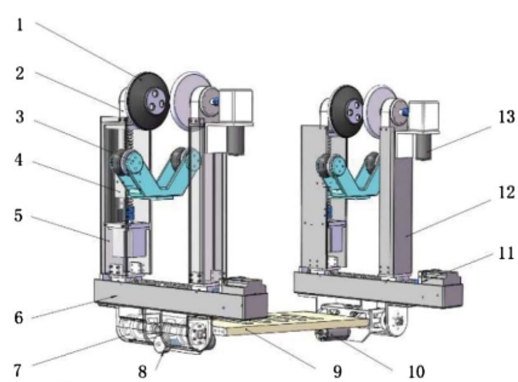


Fig. 39 Inspection robot structure [89]

Fig. 40 Robot body mechanism and prototype [90]

aid facility (called a "bridge") is needed to assist the robot through the corner tower.

In reference [91], the design and implementation of a new transmission line inspection robot named LineSpyX is introduced. In this study, a solution based on digital radiography (DR) is presented for the solution of the Non-Destructive Testing (NDT) problem of Air Aluminium Conductor Composite Core (ACCC) wires. The proposed robot consists of a body, mobile system, NDT system and various functional components (Fig. 41). LineSpyX's drive system consists of two independent rubber wheels, and the driving force is provided by geared DC motors. Thanks to its wheeled movement system, the robot moves on wires, overcoming obstacles such as vibration dampers and grippers. Thanks to NDT, internal defects of ACCC wire are detected. The robot motion system has been optimised with theoretical and simulation analysis. The essential functions of the developed robot have been verified by laboratory experiments and field tests.

In reference [92], precise motion control of an inspection robot on a power transmission line is presented, taking advantage of the time delay control and pole placement based state feedback control. The system has two identical arms, two grippers, and a trunk. DC motors called ADJ and ROL are used to drive the triangle clamp system and wheels (Fig. 42). The cylindrical arms are driven by motors called ROT to adjust the obstacle crossing sequence. In the study, only CAD drawings of the inspection robot are given. It has been stated that the simulation study of the selected control algorithms showed stability and robustness for precise motion control of the inspection robot.

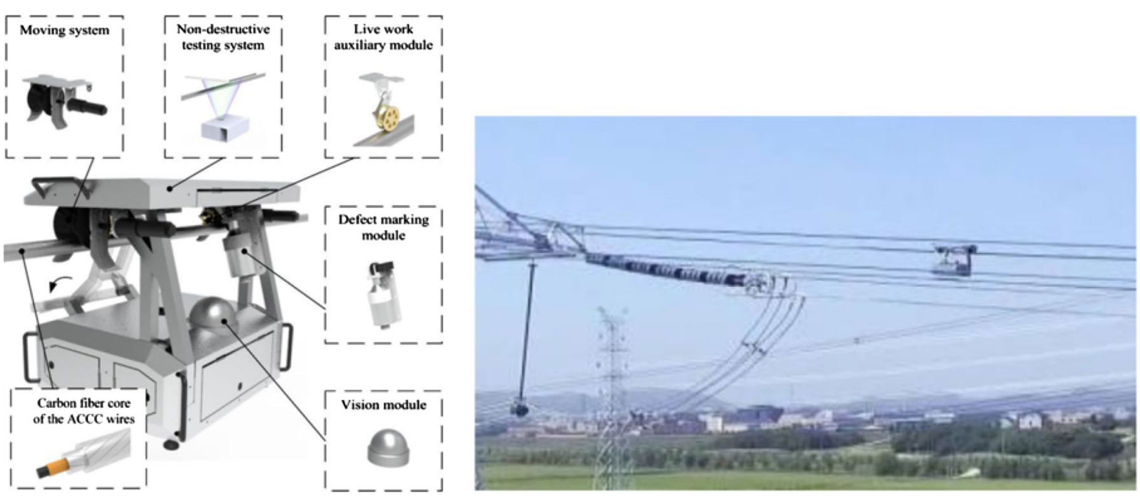


Fig. 41 Hardware architecture of LineSpyX and field tests [91]

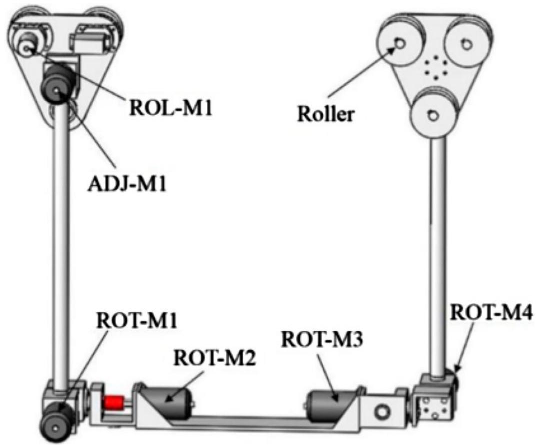


Fig. 42 The structure of the dual-arm robot [92]

The summary information of the inspection robots that can move on single wires the compiled is shown in Table 2.

3.2 Robots Moving on Ground Wires

Supported by China's national high-tech research and development program, the team at SIACAS (Chinese Academy of Sciences) focused on developing mobile inspection robots. Three serial prototypes named AApe-A, AApe-B and AApe-C are developed and are shown in Fig. 43 [93, 94]. The inspection robot prototype AApe-A1 was created in 2003. The inspection robot prototype AApe-A1 was developed in 2003. The robot has remote control functions such as forward, backward, and stop, transmitting the received live images to the base station [94]. Although it has the main function to inspection 500 kV transmission lines, the AApe-A1 does not have obstacle navigation.

In 2004, the AApe-A2 prototype was developed with simple obstacle navigation capability. In addition to the same functions of AApe-A1, AApe-A2 can directly pass counterweights thanks to the special design of the wheel. To navigate obstacles on the overhead ground wire, inspection robot prototypes AApe-B have been developed. In 2005, the AApe-B1 was developed, capable of performing obstacle navigation on overhead ground wire. However, AApe-B1 has high power consumption and a complex mechanism. AApe-B2 was developed in 2006 and had the following functions: proceeding on overhead ground wires with a line inclination angle of less than 15 degrees, overcoming obstacles such as counterweights and clamps, remote control of the robot such as moving forward, moving backward, and stopping, transmitting live inspection images from the robot to the ground base station. Since 2007, some cutting-edge technologies of AApe-C inspection robot prototypes have been researched. These primarily improve environmental adaptation to different barrier structures, improve operational capabilities, and increase autonomy [94].

AApe inspection robots have a double arm and wheel structure. The robot mechanism consists of a front and rear gripper, front and rear rotary joint, front and rear prismatic joint, body, and centre of the mass adjustment mechanism. Robot movements are driven by brushless DC motors. An embedded control system that can withstand strong electromagnetic interference has also been developed [93]. In the following years, some development and optimisation studies are carried out on AApe robots [95–97].

In reference [36], an inspection robot prototype is presented for the ground line shown in Fig. 44a. The robot can move along its unobstructed travel path, including a reshaped suspension clamp, and damper clamp, and overcomes the flexible, variable curvature tension bridge (Fig. 44c). The robot consists of two front and rear arms, two front and rear wheels, an expandable middle arm, and body. The robot converts solar energy into electrical energy thanks to the solar panels on its body. Field tests have proven that the prototype can autonomously perform ground line inspection and overcome obstacles.

In reference [98], the design and prototype implementation of "Cable crawler", a mobile teleoperation robot that moves on an overhead ground wire for the inspection of power transmission lines, is presented. The innovative mechanism allows both tower-to-tower movement and autonomous crossing the top of the tower and smaller obstacles. The robot shown in Fig. 45 consists of a chassis and six motorised rubber-coated rollers, two in the horizontal position to take the weight and four in the vertical position. Rubber coated rollers are driven by DC motors. The four vertical rollers are pressed onto the wire by springs, ensuring less slippage in difficult situations. The robot weight (58 kg) and the ability to pass only small obstacles are specified as features that need improvement. The study presents the detailed design of the components and successful tests with the prototype.

Reference [99] describes the development of a mobile inspection robot that can overcome obstacles such as torsion towers, suspension clamps and counterweights to automate checking for defects in the power transmission line. The mobile robot can walk on the overhead ground wires in the 500 kV power tower. The robot, which has 13 brushless DC motors, consists of two arms, wheels, claws, wrists, etc. The claws are mounted on the arms, each of which has 4 DoF. Figure 46 shows the mechanical structure of the robot. The new sensor configuration is used for the claw to grip the overhead ground wires. The bridge is mounted on the torsion tower for the robot to overcome obstacles. Experiments have been shown that the robot can perform navigation and inspection tasks.

Table 2 Robots moving on single wires

	Robot	Publication year	Description*	Weight	Figure	References
1	Shandong university, China	2005	The robot consists of five main parts: vehicle drive mechanism, brake system assembly, flexible arms, palm gripper on–off assembly, power supply and controller	45 kg	Fig. 10	[38]
2	Instituto superior tecnico and institute for systems and robotics, Portugal (RIOL)	2007	The robot consists of a central body with three serial arms	30–40 kg	Fig. 11	[50, 51]
3	Beihua university, China	2008	A robot with 5 arms, 2 prismatic hanging arms at the front and rear, and 3 arms with wheels rolling along the line in the middle	45 kg	Fig. 12	[12]
4	Hydro-Québec company, Canada (LineScout)	2008–9	The robot was designed as a 2-wheel remote-controlled vehicle	100 kg	Fig. 13	[52, 53]
5	Wuhan university, China	2010	The robot has 5 joints, 2 arm and related mechanisms. The robot charges the batteries by taking advantage of the magnetic field in the transmission line	30 kg	Fig. 14	[36]
6	Shandong university, China	2010	The crawling robot consists of 3 arms and a balance mechanism, all of which are interconnected via a base. The arms consist of prismatic and rotational joints	*NP	Fig. 15	[17]
7	China academy of sciences institute of automation, China	2010	A 2-arm inspection robot designed by imitating the movements of monkeys. When it encounters an obstacle, it can turn around and overcome the obstacle	*NP	Fig. 16	[39]
8	KunShan institute of intelligent robot engineering, China	2009	The robot has 2 wheelless legs. It makes static walking on the line	*NP	Fig. 17	[57]
9	Shenyang institute of automation, China	2011	2-arm robot with a new wheel-arm hybrid control mechanism with the addition of a passive swivel joint on each arm	*NP	Fig. 18	[63]
10	Capital normal university, China	2011	The robot consists of a 3-coordinate swivel wheel machine and 3 suspension arms	*NP	Fig. 19	[64]
11	The electric power research institute (EPRI), America	2012	The robot can overcome through different obstacles without raising its arms	*NP	Fig. 20	[33]
12	university of KwaZulu-Natal, South Africa	2012	It's a triangular 2-armed robot. There are 2 rollers on the arms	10 kg + 10 kg payload	Fig. 21	[66]
13	University of California, America (SkySweeper)	2013	Robot arms consisting of 2 elbow joints have clamps. It turns 180° and passes over the obstacle	*NP	Fig. 22	[68]
14	Chinese academy of sciences, China	2013	The robot consists of 2 symmetrical arms and a wheel with a gripper on each arm	*NP	Fig. 23	[40]
15	Monash university, Malaysia (Robonwire)	2013	The robot has 3 arms with two joints. Obstacle avoidance is achieved by alternately rotating the arms laterally	*NP	Fig. 24	[70]
16	Xian Jiaotong university, China	2014	A new three-armed robot with dual-parallelogram architecture (DPA)	*NP	Fig. 25	[71]
17	Changchun university of science and technology, China	2014	The robot has a three-arm suspension structure	50 kg	Fig. 26	[72]

Table 2 (continued)

	Robot	Publication year	Description*	Weight	Figure	References
18	EPRI Shandong, China	2014	The robot consists of 3 arms and there is a motorized rubber wheel at the end of each arm	30 kg	Fig. 27	[73]
19	Federal university of Uberlândia, Brazil	2010–15	The robot has 2 pairs of identical legs, one at the front and one at the back, and hooks (feet) attached to each leg end, allowing it to hang on the wire	8 kg	Fig. 28	[74, 75]
20	Shanghai Jiao Tong university, China	2015	The robot consists of 2 wheels driven by two DC motors and a rotary joint for each arm	35 kg	Fig. 29	[76]
21	Shenzhen Graduate School, China	2015	The robot consists of 2 support arms, an auxiliary arm, and a control box	*NP	Fig. 30	[77]
22	The Chinese university of Hong Kong, China (LineBot)	2013	The robot consists of a pitch joint, 2 active arms and 2 gripping arms	40 kg	Fig. 31	[78]
23	Innopolis university, Russia	2016	The robot consists of 2 dual-motor traction wheels, an arm and a gripper frame, and a middle frame connecting the first two frames	*NP	Fig 32	[81]
24	Chinese academy of sciences, China	2016	Imitating people climbing trees, the robot consists of 2 traction arms and 2 master arms	*NP	Fig. 33	[82, 83]
25	Universidade Federal de Minas Gerais, Brazil (POLIBOT)	2017	It consists of three modules or units: arm, traction, and support	9 kg	Figure 34	[84]
26	Xi'an Jiaotong university, China	2019	According to the simplified gibbon model, the mechanical structure of the robot is divided into three modules: shoulder, claw, and movable module	*NP	Fig. 35	[85]
27	National institute of technology Calicut, India	2019	Robot consisting of 2 robotic arms and pulley mechanism	12 kg	Fig. 36	[86]
28	Southeast university, China	2019	A two-link brachiation robot system. The ends of the arms have clamps	*NP	Fig. 37	[87]
29	Istanbul Sabahattin Zaim university, Istanbul Technical University, Turkey (ROSETLineBot)	2019	The robot has two wheels, one for the actuator and the other empty. Obstacle passage is achieved by the opening (widening) of the spring between the wheels	*NP	Fig. 38	[88]
30	Southeast university, China	2019	The robot consists of two crawling wheels, two clamping mechanisms, ball screws, two crawling arms, stepping mechanism, worm gear drive mechanism, stepper motor	35 kg	Fig. 39	[89]
31	NARI group corporation (SGEPRI), China	2020	The robot has a 3-arm structure. The front and rear arms are designed to roll forward	60 kg	Fig. 40	[90]
32	Southeast university, China (LineSpyX)	2020	The robot has a wrapped body. There are 2 wheels inside the body. Detects internal defects in wire based on Digital Radiography	25 kg	Fig. 41	[91]
33	Jiaotong university, China	2022	The robot has two symmetrical arms and grippers at the ends of the arms	Total weight *NP	Fig. 42	[92]

*In some studies, information about the weight, arm structure and other parameters of the robots are not provided (NP)

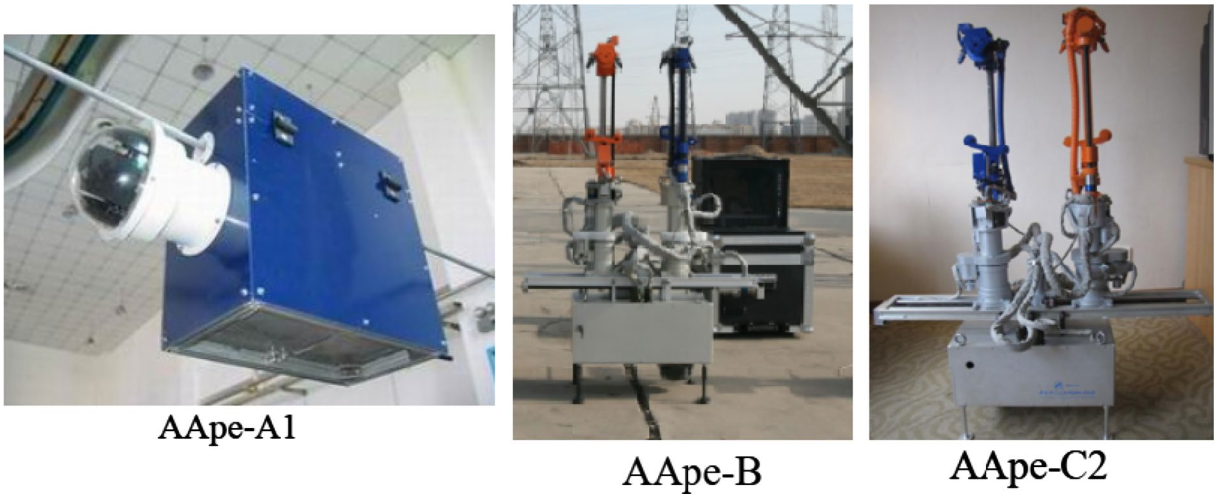


Fig. 43 AApe-A-B-C robot prototypes [93, 94]

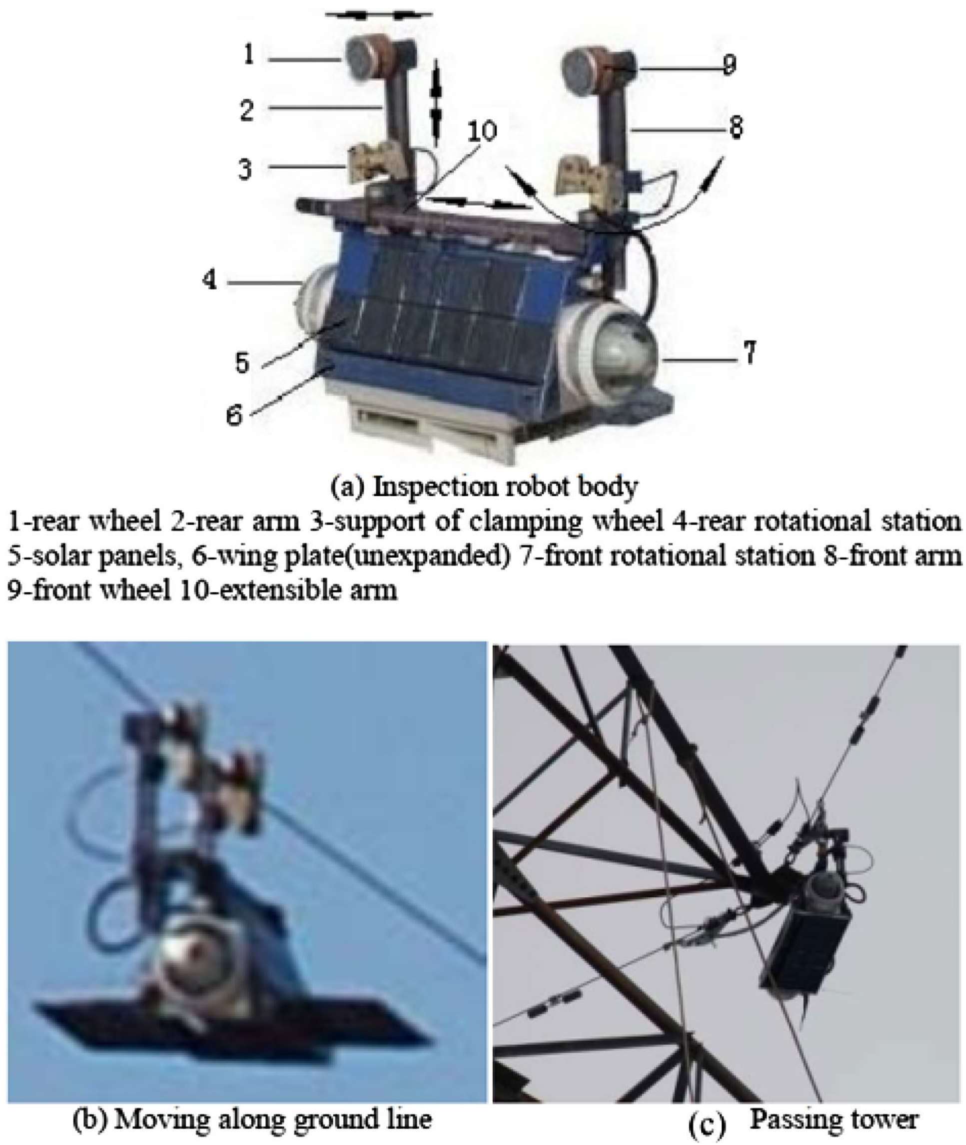


Fig. 44 Autonomous inspection robot for ground wire [36]

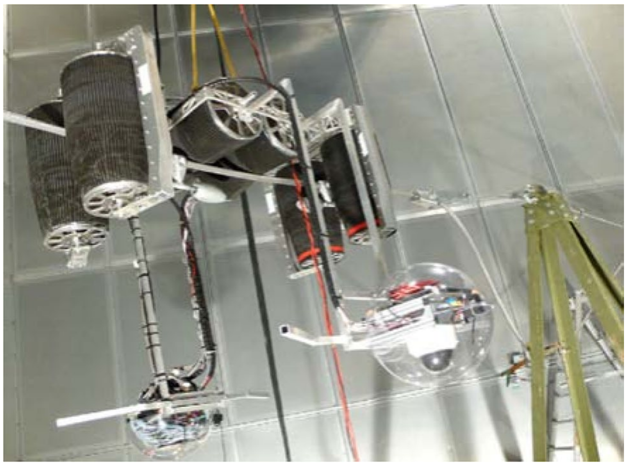


Fig. 45 Robot prototype [98]

In reference [100], a robot concept that offers low-cost maintenance, inspection, and easy operation is presented (Fig. 47a). The robot moves along the ground wires and goes from one tower to another. The robot consists of two fixed arms and moves along the cable using two wheels on the arms. The robot system has been developed to walk, return, and stop in a remotely controlled manner. Robot movements are driven by DC motors. In case of any malfunction in the robot, the recovery system is still being developed.

In reference [101], a new prototype of FURNAS' robot for transmission line inspection is presented. Development of the new prototype is shown in Fig. 47b. The new system combines weight reduction, low power consumption, high battery load capacity, simple structure, and operation. The study demonstrates the analysis of the potential use of the robot prototype for field testing and transmission line inspection.

In reference [2], a transmission line inspection robot design that walks like a caterpillar along the ground wire is presented. Robot: It includes components such as a power system, motion control system, communication system, sensing instruments, two caterpillar rails, auxiliary rollers, two support rollers. The general structure of the caterpillar robot is shown in Fig. 48. The caterpillar rails are on both sides of the robot and firmly compact the ground line. The cylinder and hollow cavity at the bottom of the robot

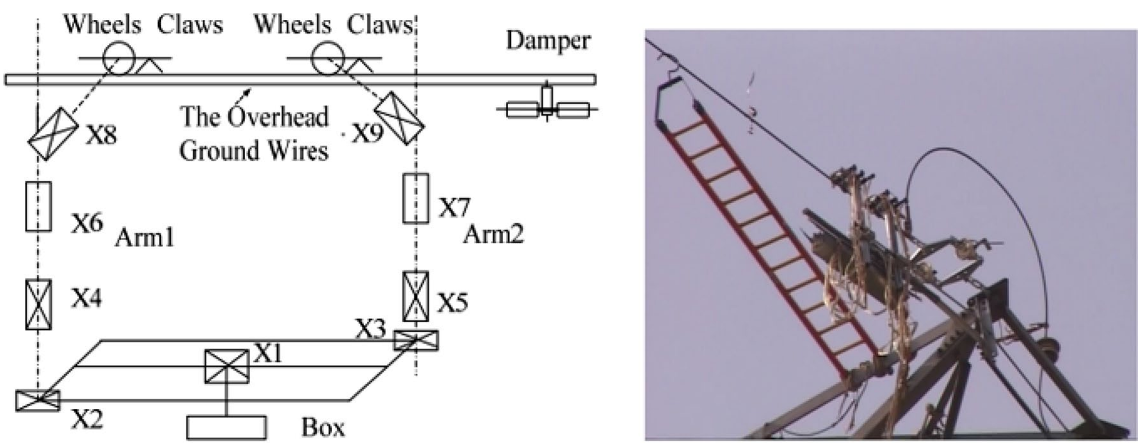


Fig. 46 Inspection robot mechanical structure and experiments [99]

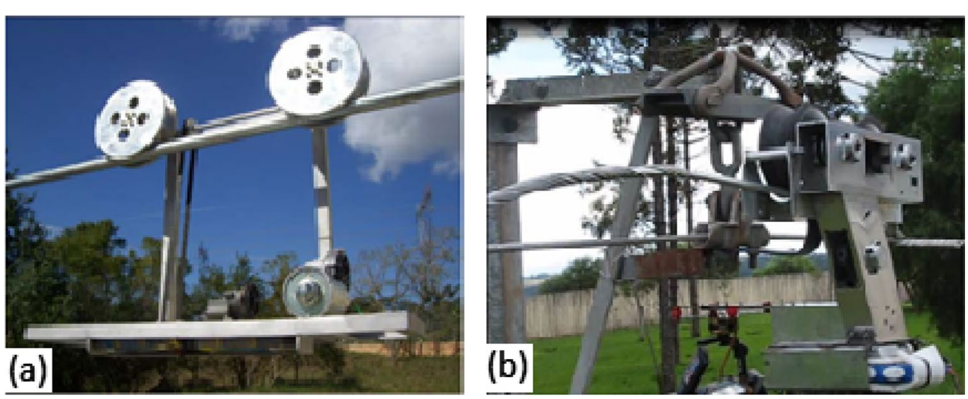


Fig. 47 **a** First FURNAS robot prototype **b** new robot prototype [101]

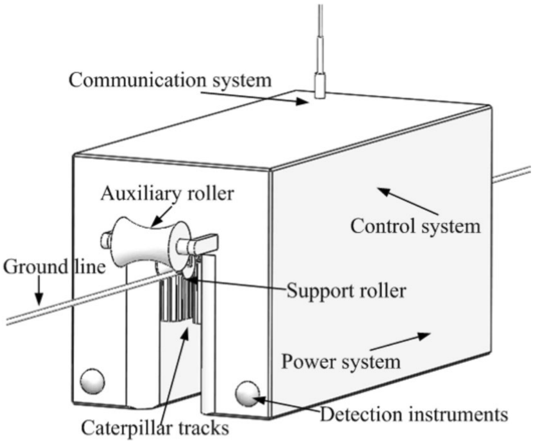


Fig. 48 Robot structure with caterpillar rail [2]

can help the robot effectively overcome obstacles such as counterweight. The auxiliary roller and the side wall of the hollow chute can help the robot to return to the right path to overcome obstacles in case of shaking of the chamber. The support roller is used to support the weight of the robot and prevent the caterpillar tracks from being pulled off the ground line under gravity. An auxiliary bridge is needed for the robot to pass through the torsion tower. Mechanical simulation analysis of the robot has been performed for a 500 kV transmission line. However, only the CAD model of the robot is presented in this study.

In reference [102], the design and analysis of an innovative review robot (called LinBot) is presented. The purpose is to check the phase lines and detect faults by moving on the ground wires of the transmission lines. Thanks to the active and passive mechanisms in its structure, the robot can overcome all different ground wire obstacles. Active mechanisms consist of four vertical cylinders, three horizontal cylinders connected to the robot chassis by four arms, and six mechanisms that control the vertical position of these horizontal cylinders (Fig. 49). DC motors drive seven cylinders. In addition, four sets of rotary springs and vibration dampers are passive mechanisms at the joints of the vertical roller arms. A simulation study is conducted at ADAMS to verify the robot's stability and feasibility in obstacle avoidance. The simulation results of the dynamic behaviour of the robot, including the motor torques, are presented. In addition, the effect of wind on the stability of the robot is investigated. The functional performance of the robot prototype has been experimentally evaluated in the real field.

In reference [103], a five-armed robot that can be separated from the line independently during obstacle crossing is proposed for transmission lines supervision. In later work [20], a new four-unit three-arm serial robot mechanism is proposed (Fig. 50). The robot mechanism meets the inspection requirements along the overhead ground wire. Designed for inclined motion, the robot is based on a parallelogram structure powered by cables and a single motor. The clamp-wheel connection mechanism is mounted on the arm. The new unit mechanism and robot prototype have been tested in the lab. The prototype demonstrated its ability to overcome obstacles.

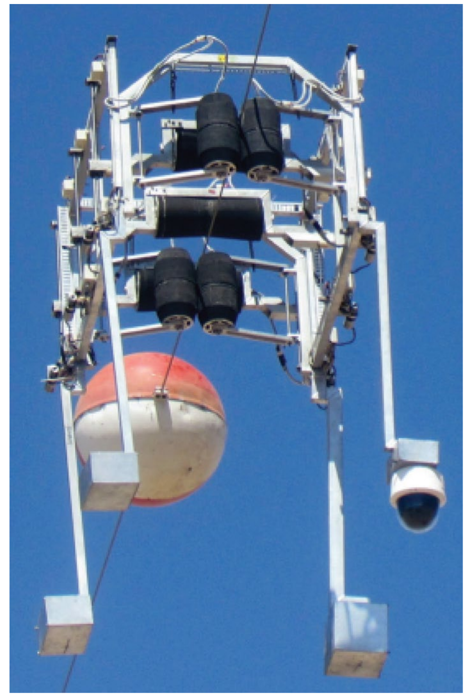


Fig. 49 Robot prototype on ground wire (LinBot) [102]

In reference [104], a full automatic inspection robot, which can overcome obstacles (dampers, flat poles, resistance-pull towers, etc.) on the overhead ground wire without any jumping motion, is introduced. With the conversion of the line, a convenient barrier-free path is built for the robot to pass, which simplifies the action of overcoming the obstacles and improves the barrier crossing efficiency. The robot consists of two wheel-arm joint mechanisms of the same structure, drive arms, grippers, locking couplings, power control box, and monitoring devices (Fig. 51). In addition, each driving arm is composed of a driving wheel device, lifting device and guiding device. As a result of the laboratory tests, it has been seen that the robot can run steadily along the line, smoothly from obstacles such as dampers, straight towers, and tension towers, and achieve the expected effect by completing the detection image of the line and its equipment.

In reference [105], a transmission line inspection robot moving on the ground wire is presented and an obstacle avoidance behaviour planning method based on multi-sensor fusion is applied. The robot consists of three independent assembly units, the rolling mechanism,

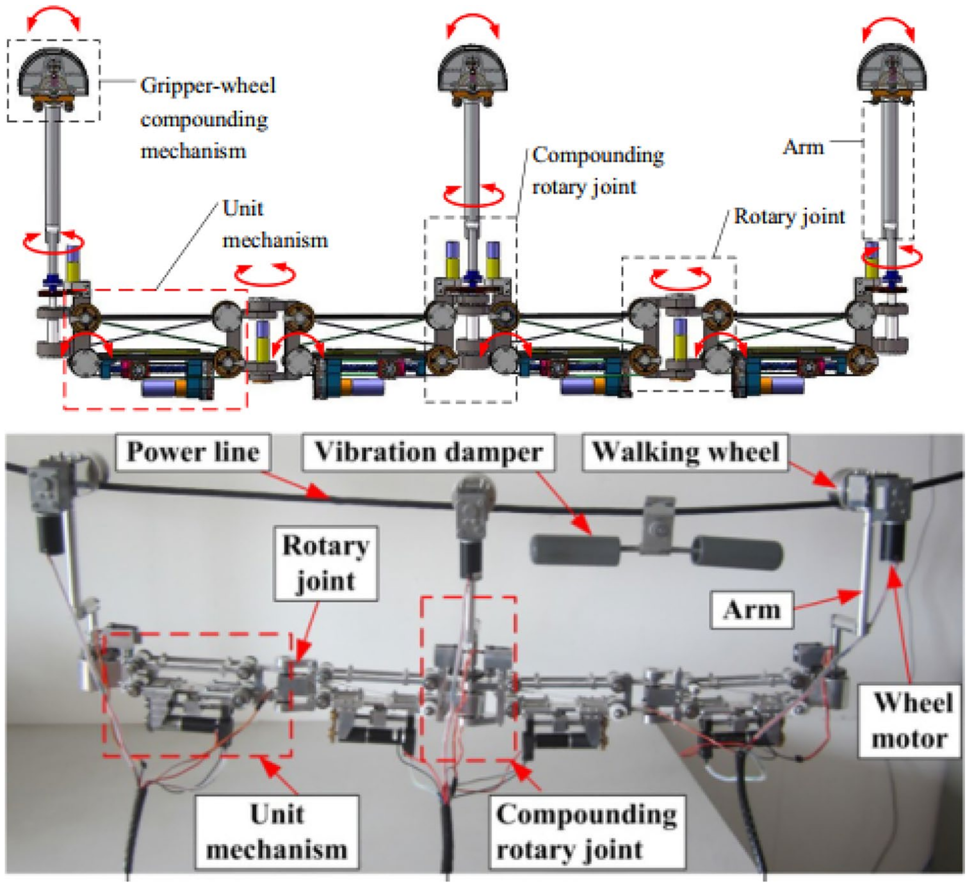


Fig. 50 Robot model and prototype [20]

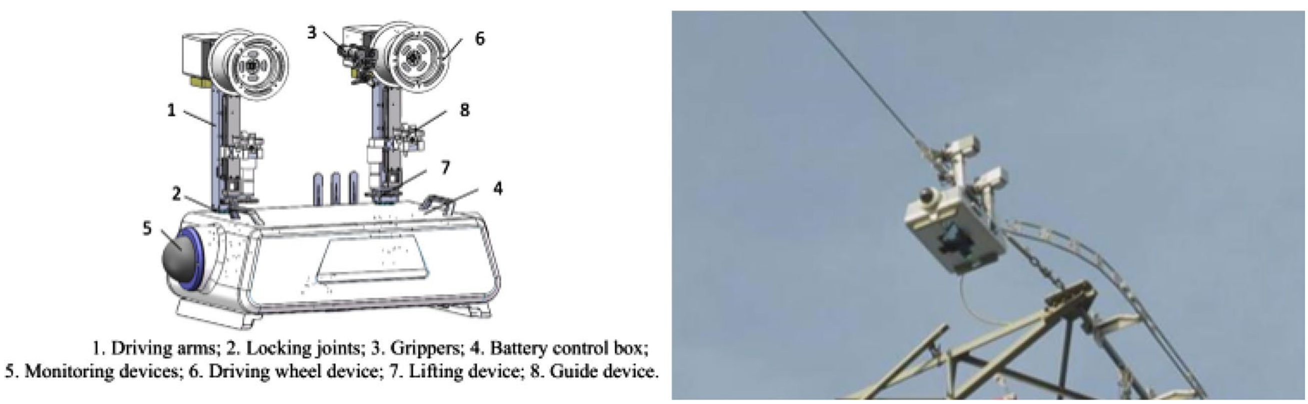


Fig. 51 Robot mechanism and online tests [104]

the clamping mechanism, and a central unit that allows them to slide and rotate (Fig. 52). The rolling mechanism includes the wheels at the ends of the two arms of the robot, and the clamping mechanism includes passive nylon pulleys located under the wheels. The rolling and obstacle-crossing movements of the robot are driven by brushless DC motors. Experiments have been performed on the lines and simulated to verify the effectiveness of the proposed method for obstacle detection and behaviour planning during transmission line inspection.

The summary information of the inspection robots that can move on ground wires the compiled is shown in Table 3.

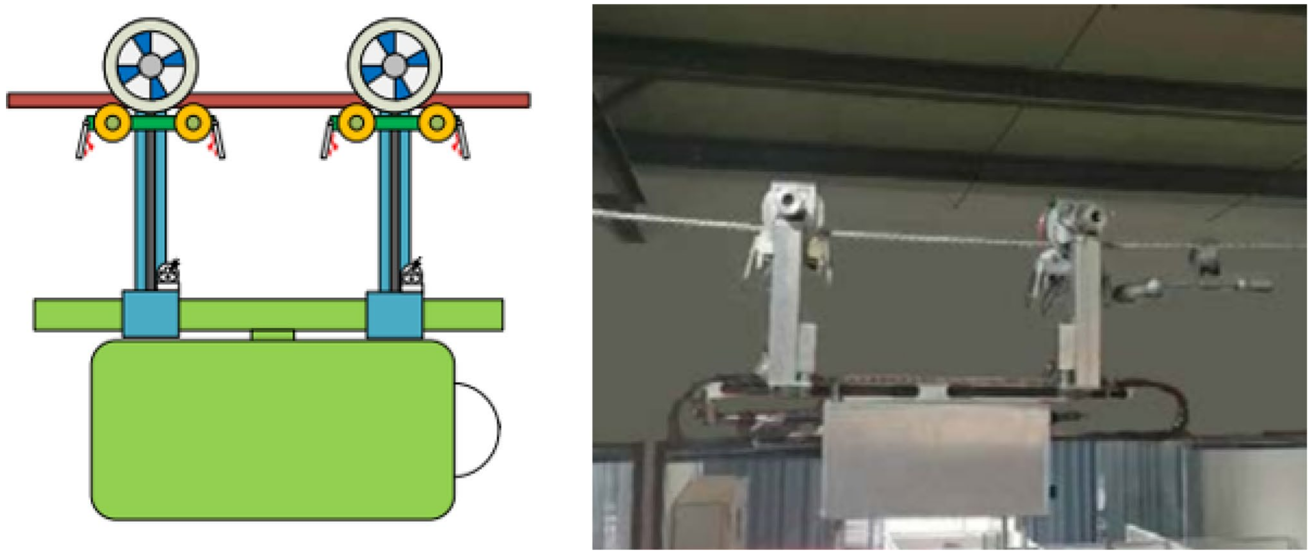


Fig. 52 Robot structure and experiments [105]

4 Challenges, Practicability and Future of Inspection Robots

This section mentions some challenges encountered in the construction and operation phase of inspection robots and some challenges related to the practicability of inspection robots. The challenges mentioned here are presented as a compilation based on studies in the literature. The challenges of inspection robots include:

Large slope walking: Inspection robots must be able to climb on slope wires in a way that consumes the least energy and provides the highest torque. In the studies in the literature, there is a robot whose climbing angle reaches up to 35 degrees [91].

Obstacle detection and positioning: For the robot to walk uninterrupted along the line, it must be able to cross the obstacles it encounters. For this, good perception is needed. In addition, detecting the exact position of the obstacle is very important for the robot to start the obstacle crossing process and ultimately cross the obstacle. The robot must contain the relevant sensors that enables it to detect and cross successfully.

Climbing and obstacle crossing: One of the most critical points in the movement process of inspection robots is obstacle crossing. The robot must be able to overcome the obstacles on the line, regardless of size.

Crossing linear tower (suspension tower, straight tower)/ tension tower: Electric transmission line towers are generally examined under two headings tension and suspension towers. In tension towers, a jumper cable is connected between two straight transmission lines, which tend to give the slight angle between the adjacent tension towers where, as in suspension towers, insulators are hung vertically, and there is no change in the angle of adjacent suspension towers [106]. For the continuity of the inspection, the robot must be able to pass through these two tower structures.

Intelligent control or independent inspection: Control algorithms are needed to stabilise robot movements. Inspection robots found in the literature can be controlled autonomously or semi-autonomously (with remote control). Currently, most of the practical control robots are controlled remotely, that is, by a human operator from the ground control centre [13]. If intelligent control algorithms are developed, perhaps by using deep learning, an independent inspection is provided by making it easier for robots to perform the inspection function.

Adaptability to the harsh weather in the field with long-term online presence in the tower: In the introduction, it was mentioned that transmission lines pass through difficult areas. Weather conditions in these regions can also be quite challenging. The robot is exposed to external factors such as wind, rain, snow, and icing. Under these conditions, the robot must be able to work without being affected by external factors and be able to perform its inspection task. For this, motion optimisation and field tests must be done well.

Online power supply with continuous endurance: Currently, all practical inspection robots are usually powered by batteries. However, the power supply was the main factor limiting the operating time of the inspection robots, as the onboard battery had to be regularly recharged or replaced. For more inspection distance, a large battery can be installed in the robot, but the larger the battery, the heavier the structure. Thus, this makes it difficult for the robot to avoid obstacles and slow it down. To improve the performance of the power supply, it is important to provide an alternative to offline charging of the battery. There are various solutions

Table 3 Robot moving on ground wires

	Robot	Publication year	Description*	Weight	Tower crossing	Figure	References
1	China academy of sciences (SIACAS), China (AApe-A-B-C)	2010	Robots have a double-armed and wheeled structure. (AApe-C1 is 15 kg.)	42 kg	No need to auxiliary bridge	Fig. 43	[93, 94]
2	Wuhan university, China	2010	The robot consists of 2 front and rear arms, 2 front and rear wheels, expandable middle arm and body. The robot charges the batteries using solar energy	*NP	Need to auxiliary bridge	Fig. 44	[36]
3	ETH Zurich (Swiss federal institute of technology), Switzerland (Cable-crawler)	2010	The robot consists of 1 chassis and 6 motorized rubber rollers, two in a horizontal position to take the weight and four in a vertical position	58 kg	No need to auxiliary bridge	Fig. 45	[98]
4	Shanghai university, China	2010	It consists of 13 motorized robots, 2 arms, 2 wheels, 2 claws, 2 wrists etc	30 kg	Need to auxiliary bridge	Fig. 46	[99]
5	FURNAS, Brazil (FURNAS's robot)	2016	The robot consists of 2 fixed arms and there are wheels on each of the arms	*NP	Need to auxiliary bridge (Moving tower to tower)	Fig. 47	[100, 101]
6	Wuhan NARI limited company, China	2018	The robot includes components such as motion control system, power system, two caterpillar rails, communication system, sensing instruments, two support rollers, auxiliary roller	50 kg	Need to auxiliary bridge	Fig. 48	[2]
7	Isfahan university of technology, Iran (LinBot)	2019	The active mechanisms of the robot consist of 4 vertical cylinders, 3 horizontal cylinders and 6 mechanisms to control the vertical position of these horizontal cylinders	68 kg	No need to auxiliary bridge	Fig. 49	[102]
8	Shenyang aerospace university, China	2019	4-unit 3-arm serial robot mechanism	12.31 kg	No need to auxiliary bridge	Fig. 50	[20]
9	State grid intelligence technology Co., Ltd., China	2020	The robot has 2 wheel-arm combined mechanisms with the same structure	*NP	Need to auxiliary bridge	Fig. 51	[104]
10	Shenyang agricultural university, China	2022	The robot has two arms, wheels and clamping pulleys at the ends of the arms	*NP	Need to auxiliary bridge	Fig. 52	[105]

*In some studies, information about the weight, arm structure and other parameters of the robots are not provided (NP) for the power problem, such as generating power by utilising the magnetic field in the transmission line, and placing solar panels on the robot platform [36].

Communication: Semi-autonomous robots usually act in wireless communication with a ground control centre. The distance of this communication varies according to the material and method used but is limited. This is a serious limiting factor in the remote control of the robot.

Special devices and methods for robots up and down the line: Various ways are followed to place the robot on the transmission line or to take it off the line when necessary. Various methods are used, such as placing the robot on the line with the help of workers and placing the robot on the line with the help of a cable extending from the ground to the tower. To make the inspection process faster and more effective, it is beneficial to perform with special methods or devices to lift the robot up and down onto the line. As an example, in the study in reference [107], an elevator system was designed to lift the robot up and down onto the line.

The processing of massive images: The sensor and camera data collected during the inspection are transferred to the ground station or any selected device. The important point here is the processing of the data. For the inspection function to be fully realised, the data must be evaluated and processed for this purpose. Therefore, applying a good image processing technique is a complementary move to the inspection function.

The explanations listed above are the points determined by inferences from the studies compiled in this paper. Additions can be made to these, and different solutions can be brought. It can be said that the future development direction of the inspection robots depends on advances in the configuration and structure of the inspection robot, intelligent control and independent inspection, the access standard for the inspection robot to enter the power grid, the processing of massive images, and the intelligent diagnosis of the inspection robot.

5 Conclusion

In this study, power transmission lines inspection robots are examined. There are many robots with various structures and functions in the literature. In this study, robots are grouped as those moving on the live lines and the ground wires. The robots moving on the live line are grouped as those moving on single and multiple lines. Thanks to this grouping, which is different from the previous compilation studies, the power transmission line inspection robots are listed in a clearer way.

Since the robots moving on the live line pass over or very close to the components on the line that are desired to be inspected, the cameras and sensors in these robots do not require high quality sensing. Robots moving on the live line can generate the energy they need by using the magnetic field formed around the line. However, as the magnetic field of the line, linked to the current being transmitted, can significantly vary and would not be a very predictable source of energy, it is not helpful to generate electricity by this method. For the motors, cameras, or sensors on the robots not to be affected by the magnetic field, the outer surface of the robot must be made in the form of an electromagnetic shield. There is many equipment, such as dampers, isolators, clamps (tension and suspension clamps), spacers, splicing sleeve, towers, and other electrical equipment on the live line. Robots moving on the live line have to overcome all these obstacles. Large-size obstacles have large spans, so it is more difficult for robots to overcome them. While most of the robots in the literature can overcome small-sized obstacles, studies are ongoing to enable them to overcome large-sized ones. And these robots' motion is usually restricted to the motion from one tower to the other. Dampers, suspension clamps, and spacers can be given as examples for small-sized obstacles.

Robots moving on the ground wire are further from the transmission line and the components to be inspected than robots moving on the live line. To provide a good detection and inspection, the cameras and sensors in the robots must have high quality sensing. Commonly, the ground wire has only tower tips and clamps as obstacles, in some areas, warning spheres and dampers are also placed. Therefore, the number of obstacles to be overcome by the robots moving on the ground wire is less compared to the live line. Thus, these robots can move uninterruptedly over successive tower tips. Since the robots moving on the ground wire are far from (above) the transmission line, they are also far from the magnetic field. Thus, they are less affected by the magnetic field than robots moving on the live line. Therefore, there is no need for electromagnetic shielding of the robot; only shielding of the electronic components on the robot is sufficient. Accordingly, there is no need for potential equalization between the line and the robot. Since shielding is required for robots moving on the live line, the size limitation is less critical, but robots moving on the ground wire must be small to further reduce the possibility of being affected by the magnetic field. This is another reason why shielding is not needed. Also, using the ground wire for inspection is safer than using the live line.

The advantages and disadvantages of robots moving on the live line and ground wires have been determined as above considering the examined robots. Observed inferences are shown in Table 4.

Robots that can move along power transmission lines and overcome obstacles are seen as a good alternative for line inspection. Inspecting transmission lines, which must pass through regions such as forests, deserts, highlands, and

Table 4 Advantages and disadvantages of robots moving on live line and ground wire

	Advantage	Disadvantage
Robots moving on live line	Cameras and sensors do not require high-quality sensing Energy can be obtained from the magnetic field	Electromagnetic shielding is mandatory The number of obstacles to overcome on the line is too many
Robots moving on ground wire	It is sufficient that only the electronic part is resistant to the magnetic field and static field protection The number of obstacles that need to be overcome on the line are very few No potential equalization is required Ground wire is safer than live line	Requires high-performance cameras and sensors They need to be smaller in size (to be less affected by the electromagnetic field)

seas, is quite inconvenient and challenging. Physical conditions and line lengths are the main contributing factors. Traditional line inspection methods made by the workers themselves and by helicopter are not practical today. The most critical parameters in the transmission line inspection process are safety, cost, speed, and efficiency. Robots are highly effective due to their remote control, ability to move independently on the line, overcoming obstacles, and providing information about the line status through cameras and sensors. Therefore, it can be said that the use of transmission line inspection robots is one of the most appropriate methods to inspect the transmission line and its accessories. All methods used in power transmission line inspection should be evaluated and compared in every aspect to reach a definitive judgment. However, beyond simple visual inspection, the development of sensors, cameras, and data collectors to reflect the line status is a support that will increase the value of inspection robots. Thus, they may perform a condition assessment of steel core wires of aged Aluminium Conductor Steel Reinforced (ACSR) conductors, detect and locate broken wires, measure the remaining cross-section of steel wires [16]. Some of these supports can be listed as follows: corona camera, thermal camera, corrosion detection sensor, broken wire detection sensor, insulator crack detector, etc. In addition to these, supports such as optimising the robot structure, intelligent control, independent inspection, operability under the influence of wind and adverse weather conditions, long life battery, and massive image processing are also crucial important. According to the CIGRE Technical Brochure, the four future states for transmission line robotics technologies are as follows: Autonomous Inspection, Automated Construction, Field Worker Support, Remote Repair, and Refurbishment.

As a result, it is inevitable to say that line inspection with inspection robots is more effective than traditional methods, at least supporting traditional methods. Our main goal is to review the commonly used transmission line inspection robots; and determine whether they can be used or not, and which robots are better for different situations based on their advantages and disadvantages. In addition, in the study, the contribution of robotic systems to inspect transmission lines has been revealed. This comprehensive literature review is presented in the hope that it will help and guide further research.

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Data Availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical Approval The submitted work is original and not have been published elsewhere in any form or language.

Consent to Participate Every author provided consent to participate.

Consent for Publication Every author provided consent to participate.

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