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Robotics in Power Systems

Enabling a More Reliable and Safe Grid

Power systems face numerous challenges to address the growing need for sustainable energy worldwide. Several tasks directly focused on power systems operations can be either partially or completely automated by an unmanned or teleoperated robotic system. Robots can improve efficiency, reduce labor costs, and, most importantly, avoid operational risks, since power plants and transmission lines are hostile environments for humans. Although there has been some preliminary development of robotic applications in several tasks related to power systems, the technology is still undergoing research and development; it is highly dependent on the nature of the tasks to be performed, and a unified framework of applications does not yet exist. The aim of this article is to present the main contributions from the robotics field to the inspection and maintenance of power systems through the analysis of state-of-the-art and current

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advances, thus providing the reader with a comprehensive and insightful analysis of implemented examples and future trends.

The History of Robotics in Power Systems

In recent years, the demographic and economic expansion of countries has led to an increase in the demand for electrical energy, thus requiring larger and more complex power systems. This complexity has a direct toll on inspection and maintenance tasks, and the occurrence of blackouts in different electrical networks worldwide has exposed the vulnerability of power systems. A clear example of the fragility of power systems occurred on 24 September 2011 in Chile: a fault in the 500/230-V transformer from an electrical substation in Ancoa caused a blackout of the national power system. The outage affected approximately 9 million people and interrupted normal operations in several copper mines, which had an immediate impact on the local economy [1].

Power systems require constant inspection and preventive maintenance for proper fault-free operation [2]. Supervising the different power system stages is a complex task. Performing maintenance while the systems are deenergized would alleviate the operative risks, but it would also create problems in a society that demands a full availability of service [3]. Helicopters are currently used to carry out inspection and maintenance work in power systems [4], [5], as these procedures can be performed on energized lines without interrupting service. However, since power systems are hostile environments and are often mounted in inaccessible locations, the inspection and maintenance work is sometimes dangerous and insecure for the technical personnel, limiting the surveillance process performance. These disadvantages make robotics a more attractive option for a wide range of scenarios, including electrical substations [6], high-voltage overhead transmission lines [7], and power plants [8]. Power system robotics enables users to assess the condition and status of power system components using different autonomous or remotely controlled machines. Its main objective is to reduce or eliminate human exposure to potentially dangerous environments while collecting the data required for reliable monitoring of the power system.

Early publications regarding applications of industrial robots in power systems describe teleoperated machinery for maintenance of substation transformer and power transmission lines [9], [10]. The use of robots in the electric industry at that time focused mainly on the development of teleoperated robots for maintenance and inspection of live power lines [11]. A few years later, the first publications on mobile robots appeared addressing the security patrolling of substations [12], overhead distribution line-work manipulation, and underground cable conduit monitoring [13]. These works became the earliest validated robotic prototypes used in power systems.

Disregarding the use of robots in other situations (e.g., operation or assembling), successful case studies of robots in power systems can be classified into two groups according to the tasks they perform: inspection and maintenance. Using robots for these tasks improved the management of the electric power systems by adding new value and capabilities to the process, due to their high adaptability to different environments otherwise hostile for the human labor force [14]–[16].

An important characteristic of robots is related to industrial safety, as robots can be used for high-risk tasks during which people could be involved in accidents or mishaps. As robots are very accurate machines, they can be optimally designed to perform specific tasks with minimal errors under different environmental conditions. The growing importance of robots for minimization of risk and execution of complex tasks within power systems is addressed in [6] and [17], where the relevance and impact of this technology is underlined. Although robots are an enabling and proven technology, their application in power systems presents several open challenges [13], [18]. Several commercial systems have been developed to perform specific maintenance and inspection tasks on power systems [19]–[24]. We collected and reviewed the main contributions regarding this technology to establish the links and gaps between power systems and robotics.

Power Systems

Power systems comprise the generation of electrical energy and its transmission and distribution to the end consumer [25]. Although the size and complexity of power systems can vary widely, they all have the same basic features and structure: they operate essentially at constant voltage and frequency, and they are composed of generation, transmission, and distribution stages [26]. An example of a typical power system, including typical voltage levels and different types of users, is shown in Figure 1.

Power systems are vulnerable to several threats, which can be divided into three main groups, as shown in Table 1. Environmental threats are related to climate, temperature, and humidity, and they involve weather conditions that change over time and fluctuate seasonally, including the presence of snow, rain, wind, and dust, among other factors [27]. Operational threats are directly related to the continual use and installation of the electrical equipment [28]. Human and animal threats are related to the potential damage caused by the presence and actions of living beings [29].

The main issues related to these threats can be divided, according to their nature, into three groups, as shown in Table 1: chemical, mechanical, and electrical. Chemical issues are mainly related to pitting corrosion [30], [31], which is an extremely localized corrosion that leads to the creation of small holes in the metal, and to general corrosion, which decreases the surface uniformly [32]. Mechanical problems are mainly related to fractures or damages caused by aging or degradation of the equipment [27]. Finally, electrical problems are related to environmental discharges, which endanger not only the electrical equipment but also people [29]. These risks and issues require

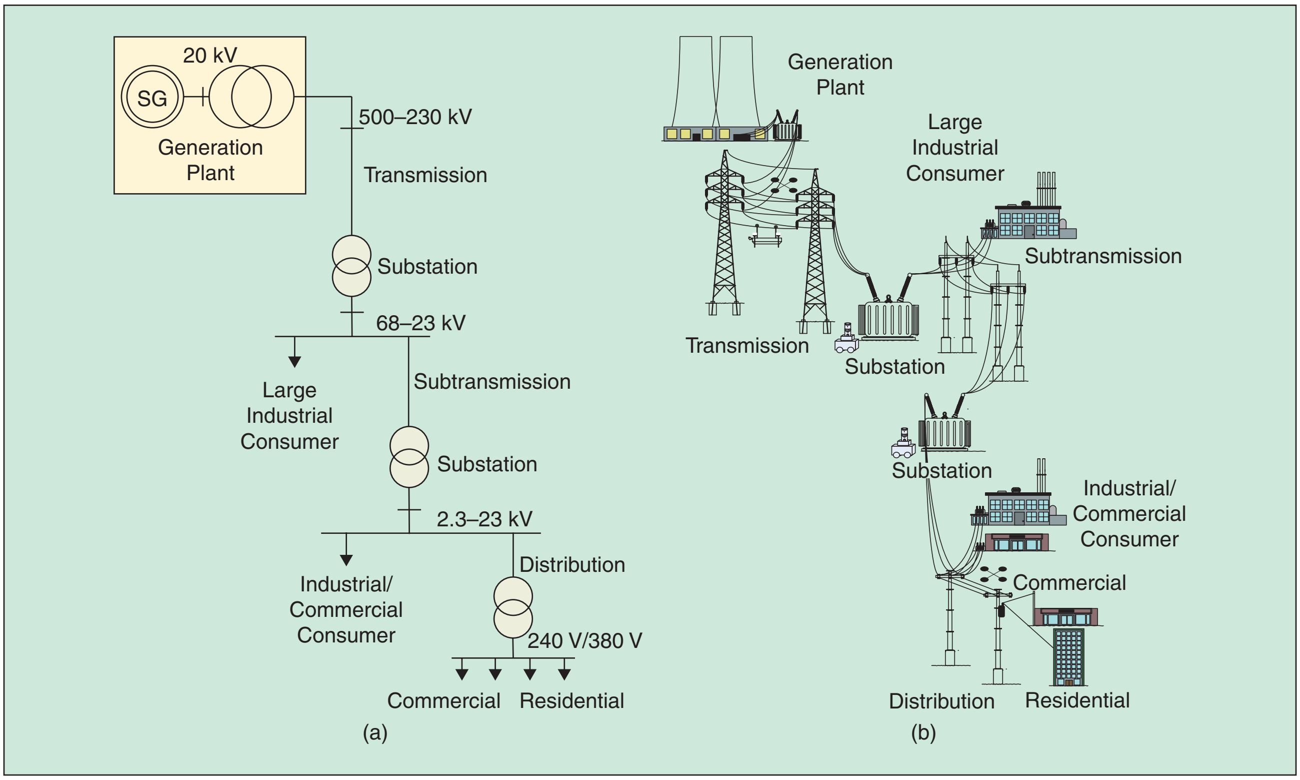


FIGURE 1 – The basic elements of a power system—the generation of energy, transportation to and through substations, and distribution: (a) a single-line diagram and (b) a structure diagram. SG: synchronous generator.

close surveillance, monitoring, and maintenance, which demand specialized hardware, human resources, and logistics. Accordingly, the main applications of robotic systems in power systems are inspection and maintenance tasks. The classification of such robotic systems is shown for inspection tasks in Figure 2 and maintenance tasks in Figure 3 and explained in detail below.

Inspection Tasks

Inspection tasks are focused on applications that do not require direct contact with the asset. Inspection robots are aimed at detecting, analyzing,

TABLE 1 – THE MAIN THREATS IN POWER SYSTEMS AND THEIR IMPACT.

MAIN THREATS		POWER SYSTEM IMPACT	
Environment	• Wind, wind and ice • Ice and snow • Salty or corrosive • Galvanic • Lightning • Earthquake	• Chemical • Corrosion	• Steel cross section • Zinc layer • Contamination • Aluminum
Operational	• Aging • Power cycling • Over current/voltage	• Mechanical	• Fatigue • Creeping • Cracking/rupture • Fretting/unfastening
Animal and Human	• Bird scat, bird nests • Woodpeckers/insects	• Electrical	• Partial discharge • Increase of resistance • Loss of insulation • Voltage reduction • Overheating

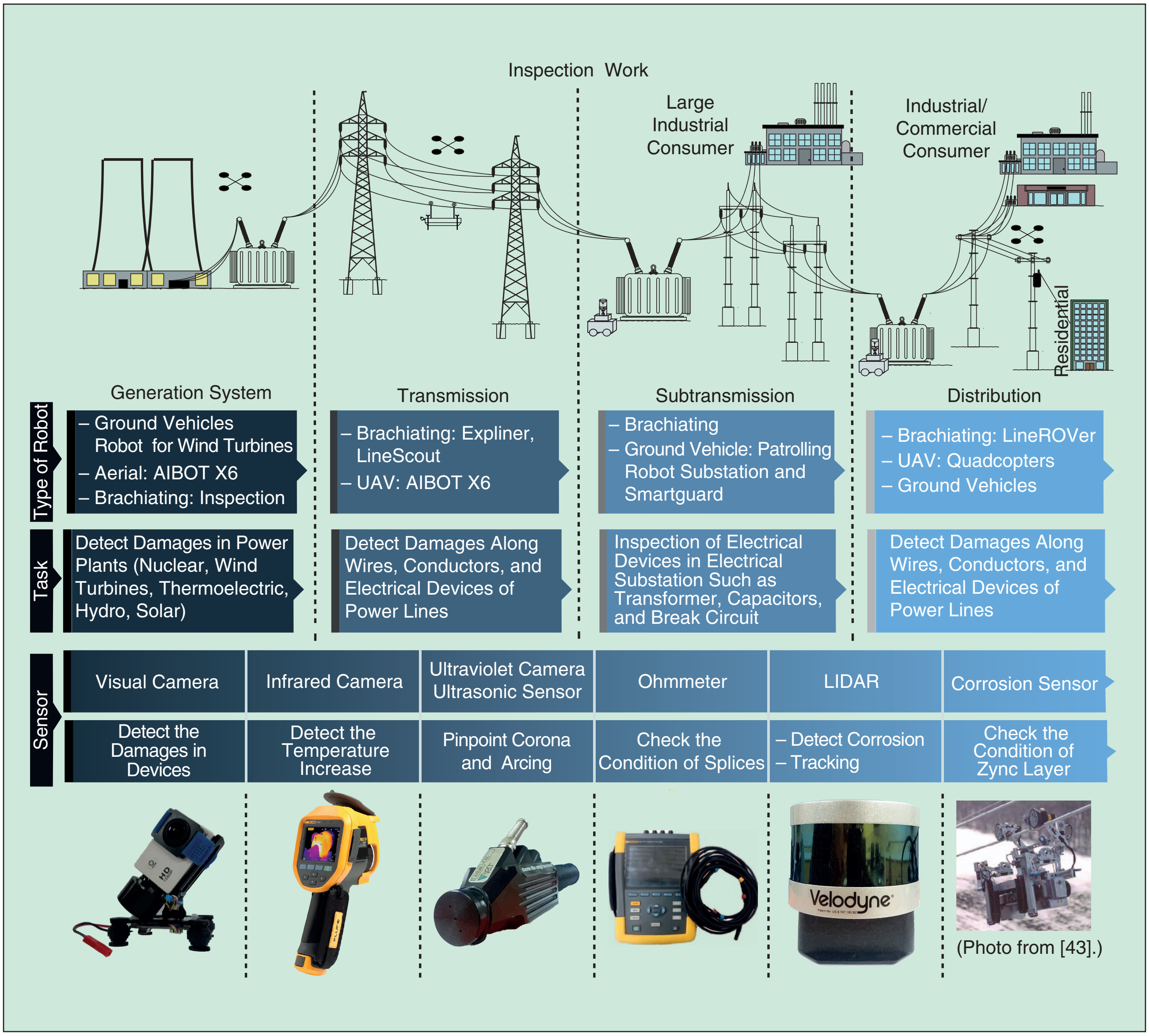


FIGURE 2 – The robotic technology applied in power systems for inspection tasks.

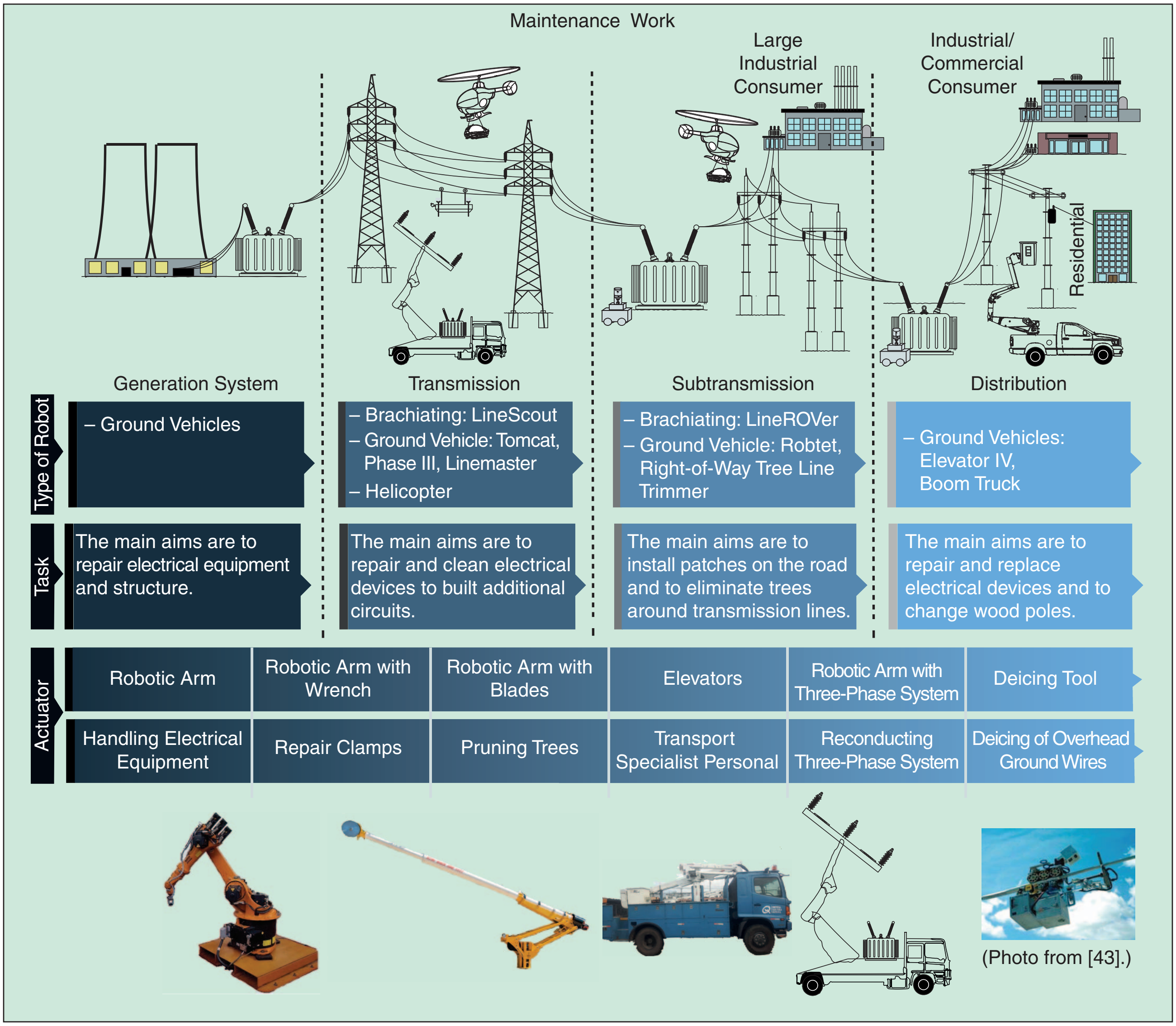


FIGURE 3 – The robotic technology applied in power systems for maintenance tasks.

and predicting failures in the electric equipment. They can be classified into three categories: brachiating robots, unmanned aerial vehicles (UAVs), and unmanned ground vehicles (UGVs), according to the needs of the power system (e.g., the power plant, transmission line, or substation).

Brachiating Robots

Brachiating robots, such as the one depicted in Figure 4, move on the conductors to inspect transmission lines or on the steel cables in the case of substations. For example, the Tokyo Electric Power Company, in cooperation with the Toshiba Corporation, designed a mobile robot for the inspection of transmission lines in 1991. This robot inspects 66-kV fiber-optic overhead ground wires (OPGWs) and navigates over a ground wire that is located above the actual power transmission lines [11]. The robot comprises a controller and power source, and it is self-propelled, with two different behavior modes: one for approximating motion using preprogrammed data concerning the tower and power line information and the other for precise positioning. The automaton is outfitted with a tower-detection sensor based on a range-ultrasonic device, a subsidiary contact sensor, a guide-rail sensing function used for contacting the ground wire (the resistance measurement of motor torque), a clamp-wheel status-detection sensor, and a guide-rail hook status sensor (status detection was accomplished by the interruption of the fiber-optic light source, the presence of OPGWs, and the open and closed status of the hook claw).

With the same aim, the Hydro-Québec Research Institute (IREQ) presented its first prototype of the mobile robot, called the LineROVer, in 2000. First presented as an overhead ground-wire deicing application, its capabilities were later improved in the subsequent version, which is called the HQ LineROVer [33]. The HQ LineROVer is equipped with infrared and color cameras to collect images related to temperature differences that arise from components such as compression splices and insulators, with the aim of detecting hot spots and potential problems [34]. Currently, IREQ has developed a commercial system for performing inspection tasks on the transmission grid based on LineROVer technology [20].

In 2006, IREQ developed a new platform named LineScout. The main feature of this robot was its capacity to clear obstacles as it traveled down a line [35]. It can move along several axes, allowing it to adjust its shape in real time to various line configurations and to a wide range of obstacles while remaining as light and compact as possible. It has a robotic arm with a camera for the visual inspection of line components, which allows for splice condition evaluation and some live-line working. The implementation of programmable pan-and-tilt camera units and a dual-end effector robotic arm (the LineArm) to work on bundled conductors was annexed later [36]. The use of light detection and ranging (LIDAR) UTM-30LX for obstacle detection on power line conductors is described in [37] and [38]. Since its launch, LineScout technology has progressed; Hydro-Québec, through its research institute IREQ, presently conducts the development, manufacture, and sales activities for the overhead transmission-line inspection robot [21].

In 2008, the Kansai Electric Power Corporation (Japan), the Japan Power Systems Corporation, and HiBot Corporation presented a robot named Expliner, which was designed for the remote inspection of powered high-voltage transmission lines [39]. The robot was composed of motion units (two shafts, each with two pulleys), a base (actuators of the vertical poles), and a manipulator and counterweight. The Expliner was able to detect the ruptured strands using two charge-coupled-device minicameras and a mirror assembly, and it was also able to detect corrosion by employing laser sensors to measure the diameter of the cable. Since 2014, Hitachi High-Tech, in conjunction with Hitachi High-Tech Fine Systems, has been working to develop a commercial prototype based on this technology [22].

The State Grid Shandong Electric Power Research Institute (EPRI; the Electric Power Robotics Lab), in association with the State Grid Shandong Electric Power Company (Grid Maintenance Department), designed a brachiating robot for the inspection of overhead transmission lines in China [40]. The system was composed of three arms, two equipped with a gripper designed to clamp firmly onto the conductor to secure the robot.

The University of Shanghai for Science and Technology developed a robotic system for the inspection of 500-kV transmission lines [41]. The system walks on OPGWs in a 500-kV power tower and can evade obstacles while it inspects and supervises the electrical equipment. A ground-based station remotely controls the robot.

The EPRI has been focused on the development of an automaton capable of crawling over conductor-shield wires along an 80-mi corridor. The system takes advantage of power harvested from power conductors, supplemented by power from onboard solar panels for running its motors. The system identifies nearby trees that could pose a risk to wires, evaluates right-of-way encroachment, and assesses the status and condition of the electrical equipment using high-resolution cameras [42].

Periodic inspection of the insulators in power transmission lines is required to prevent failure, which has been known as a major cause of power failure. The Korea Electric Power Corporation developed a robotic system for live-line suspension insulator strings [29]. The main aim is to prevent insulator failure in 345-kV power transmission lines. The robot structure is very simple, small, and lightweight and uses a wheel-leg mechanism for moving along a suspension insulator string. A summary of the most relevant brachiating robots, including technical characteristics and central applications, is provided in Table 2.

UGVs

Ground vehicles are also used for power systems. Their corresponding maneuverability features are completely different from brachiating robots, making them more appropriate for different tasks [44]. For example, the Chubu Electric Power Company developed a patrolling robot for the supervision of substations [11]. The robotic system navigates around the substation with electromagnetic guidance, following a wire buried 1 cm below the surface.

Since 2002, the Shandong EPRI has been developing a mobile robot for inspection of substation equipment, named SmartGuard [6]. SmartGuard is composed of a robotic platform and a data center. The motion control module consists of four wheels for navigation, two for traction, and two for heading. A magnetic guiding system, presented in [45], acts as a localization system for the SmartGuard. It consists of magnetic markers placed in a roadway that serve as a reference for the vehicle. The positioning is accomplished using radio-frequency identification technology. The robot features a vision system composed of a near-infrared illumination subsystem, an omnidirectional imaging

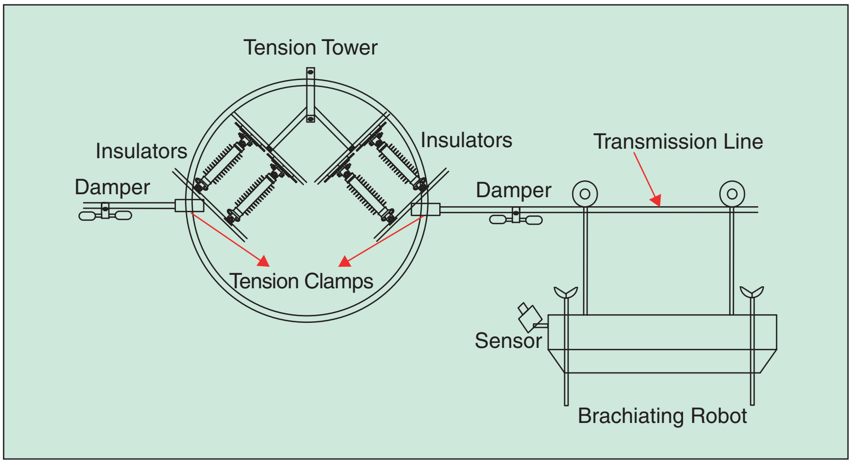
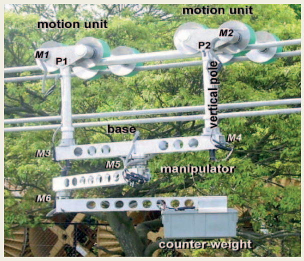


FIGURE 4 – The brachiating robot on a transmission line.

TABLE 2 — EXAMPLES OF BRACHIATING ROBOTS USED IN POWER SYSTEMS [43].

TYPE OF ROBOT	EXAMPLES OF BRACHIATING ROBOTS		
Name	LineROVer	LineScout	Expliner
Research group	IREQ	IREQ	HiBot Corp. and Kansai Electric Power Company
Year	2000	2006	2008
Inspection sensor	• Infrared and visual camera • Corrosion sensor • Ohmmeter	• Infrared and visual camera • Corrosion sensor • Ohmmeter, ultrasonic device	• Visual camera • LIDAR
Maintenance actuator	• Deicing tool • Foreign suspender clearing tool	• Line arm with three modules: a device to measure the splice resistance, a wrench, and a device to repair clamps	• No actuators
Weight	23 kg	112 kg	60 kg
Live-line working	Yes	Yes	Yes
Resistance to EMI	315 kV to 800 A	735 kV to 1,000 A	500 kV to 800 A
Energy source	Lithium-ion battery	Lithium-ion battery	Lithium-ion battery
Battery life	45 min to 10 h (depending the task)	5 h	8 h
Harvesting energy	Yes (200 A primary/1.13 A)	No	No
Autonomy	Controlled by a user	Controlled by a user	Semiautomatic: user not need to control every single detail
Remote control range	1 km	4 km	500 m
Ambient temperature range	–10 °C to 35 °C	–10 °C to 35 °C	0 °C to 30 °C
Main applications	• Visual and infrared inspection • Verification of splice condition by measuring resistance • Corrosion detection • Deicing of OPGWs and conductors • Replacement ground wires and conductors • Conductor repair	• Visual and infrared inspection • Detection of broken strands under suspension clamps • Verification of splice condition by measuring resistance • Corrosion detection • Tightening and loosening bolted assemblies • Conductor strand repairs	• Visual inspection • Corrosion detection
Platform			

subsystem, an artificial landmark subsystem, and an image processing subsystem. The robot sees four landmarks at all times and finds its location based on triangulation. A navigation system based on infrared vision for the inspection substation mobile robot is presented in [46]. Vision systems for navigation and positioning have also been described [47], in which the robot moves on a 10-cm wide yellow inspection line on the ground beneath the power substation. Range sensors, such as LIDARs, are also used by robots in substations, although their usability is restricted to navigation purposes only [48].

The technology for solving new challenges in a substation inspection is also well established. A clear example is described in [49] of a mobile inspection robot that includes a robot body and a drive system supporting the robot body that is configured to maneuver the robot over an electric environment. The development of a teleoperated inspector is described in [50] that can tilt and lift a binocular camera and a thermometer by two telescopic rods to analyze the status of electrical equipment high off the ground.

UAVs

The use of UAVs has become increasingly popular for visual industrial inspection, since these systems can capture images in difficult and dangerous areas [15], [24]. The use of aerial vehicles for inspection tasks on power systems is a recent area of research, with many challenges. One challenge is related to navigation and altitude control around the transmission line. A solution for this problem is based on the design of the Extended Kalman Filter observer to preview the dynamic altitude of a quadrotor and control the aircraft to prevent it from maneuvering out of safe flight paths, as shown in [51] and [52]. A more conservative approach is based on proportional-integral-derivative controllers. They are designed based on the linearized model of the UAVs. This technique is applied mainly to vertical takeoff and landing processes [53].

It is common to use aerial vehicles, such as helicopters, that are equipped with artificial vision systems for inspection tasks [54], [55]. The images are processed and analyzed with the purpose of detecting faults, damage, or problems in the structure or performance of the transmission line, such as in [56] where the detection of damaged cables based on video recordings obtained from the aerial inspection of transmission lines is presented. The system detects arc marks and cut wires as consequences of lightning strokes. A brightness check system based on statistical analysis is used to detect arc marks; a shape check system based on the features of the cable is used to detect cut wires. Another application based on the same technology is used for the detection and recognition of insulators [57] or conductors [58] in a transmission grid. In the first application, the detection algorithm is modeled after a region-based active contour model to solve problems related to the existence of the local minimum and the inability to segment images with severe texture inhomogeneity. The second algorithm uses the spatial correlation between the pylon and the line for transmission-line detection. In addition, in a case study [59], a vision system mounted on UAVs can detect the distance between transmission lines, to evaluate or alert a ground operator about the distances among lines. Also, it is possible to improve the detection of transmission lines by merging several techniques, such as the Hough transform and neural networks [60], or by using and matching the data from sensors such as LIDAR with both a visual camera [61] and a stereovision camera [62].

Despite the attractiveness of UAVs, they are limited by their navigation range and endurance, mainly due to their limited battery capacity. Thus, a wireless charging system for UAVs is being developed [63]. This work aims at using wireless charging UAVs for the infrastructure inspections of transmission lines. The approach is based on a resonant circuit for the wireless transmission of energy. Another solution arises from the use of current transformers (CTs). These transformers are structurally simple, inexpensive, and easy to design [64]. Therefore, better performance can be obtained in inducting power for inspection robots from power transmission lines when using CTs.

Using the transmission lines to power the robot is a new research trend. The design of a small rotor-craft with a pickup mechanism that is equipped with an artificial vision system and based on the Hough transform so that it can detect the transmission line is presented in [65]. Robots powered by the transmission line are also described in [66]. A further description of the evolution of robotics usage in power systems, its corresponding milestones, and its impact on the power systems field is shown in Figure 5.

Maintenance Tasks

The most important maintenance tasks from a robotic, sensor, and actuator perspective are shown in Figure 3. As noted for the inspection tasks, three main types of robots are used for power system maintenance: brachiating robots, UGVs, and UAVs. In some cases, the robotic system should be installed in the live line where damage occurs.

Brachiating Robots

In general, brachiating robots are frequently used for performing maintenance work in transmission networks. Their main tasks are to repair and change electrical devices such as broken strands in OPGWs. Since this robotic technology is capable of moving along the line, overcoming obstacles, and approaching the damage [67], brachiating robots are often used to perform maintenance work in transmission networks. Their main tasks are to repair and change electrical devices (e.g., the broken strands in OGWs). In addition, when designing these robots, the voltage level is an important limitation to take into consideration since the main purpose is to work with live lines in a safe way. A clear example is described in [68], where a robotic system was designed for the installation and autonomous removal of aircraft warning spheres in OGWs of electric power lines. The robot travels along the ground wire, and its main task is to install and remove the signaling spheres. The operator is responsible for guiding the robot on the wire, thus moving the robot to the approximate position where the signaling sphere will be installed. The robot has a gripper that is used for the installation and removal of the spheres.

Korea's EPRI in 2006 presented a robot for the live-line inspection of transmission-line insulators for 345-kV high-voltage lines. The robot was designed to clean insulators, measure insulation resistance, and detect cracks. A megger connected to a live line is used to measure insulation resistance; cracks are detected by analyzing the sonic resonance frequency of the insulator generated when the robot applies some impact to the insulator [69]. This kind of robot could be used for cleaning the surface of live-line insulators without using water. The robot can also clean and inspect the surface of the live-line insulators while automatically moving along an insulator string [70].

Hydro-Québec developed a robot prototype for the construction of overhead distribution lines that offers the possibility to ascend and descend a pole by teleoperation and the installation of a preassembled cross arm at the top of a 40-ft (12.20-m) pole [71]. The robot is composed of a climbing system, a cross-arm manipulation system, and a bolting system. In addition, the University of Tehran designed a robotic system that has the same form of navigation, which aims to reduce the complexity and increase the payload of the robots [72]. Finally, climbing robots are also frequently used in the maintenance and inspection tasks of vertical structures [71]–[73].

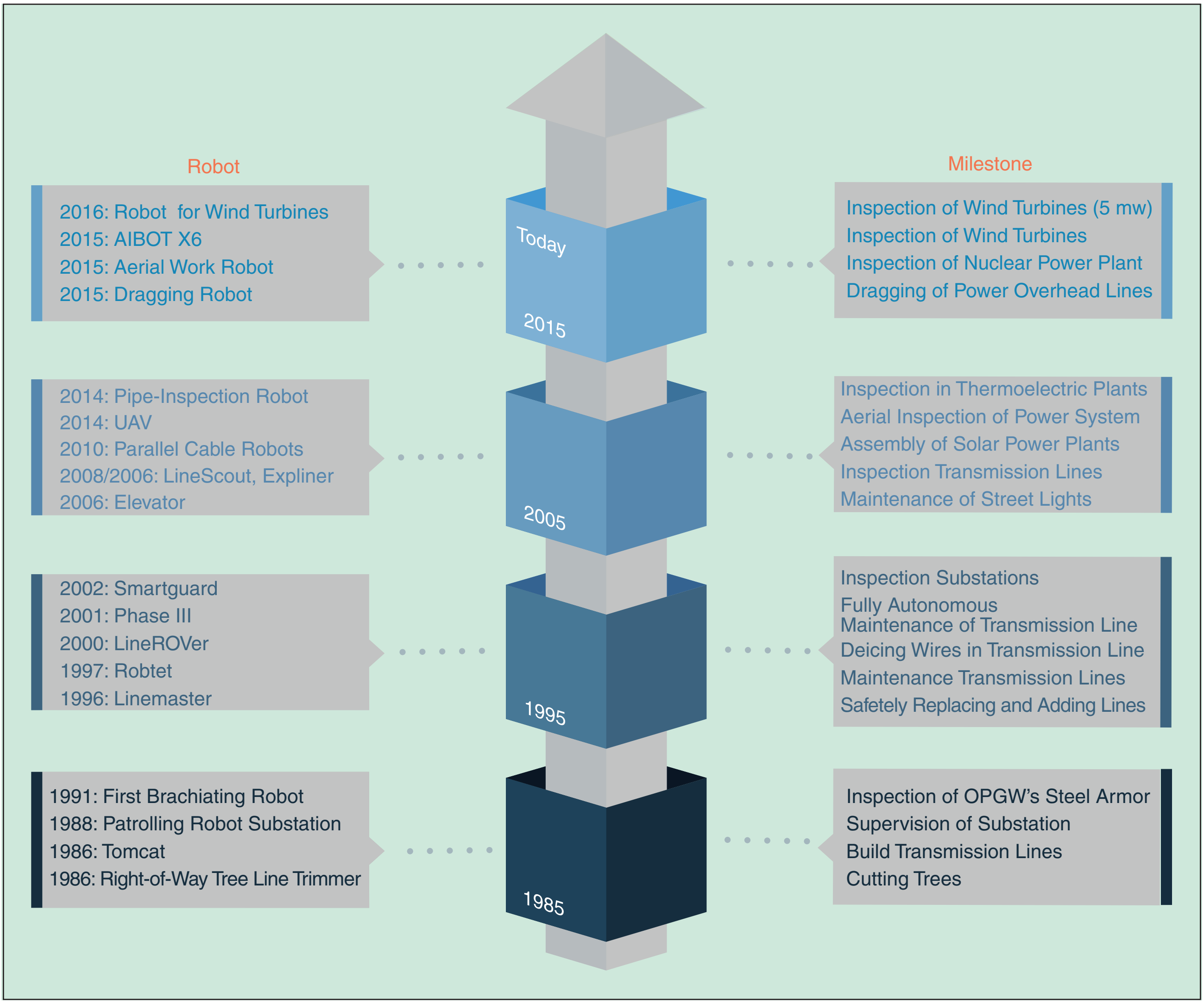


FIGURE 5 – A timeline of robot usage in power systems.

UGVs

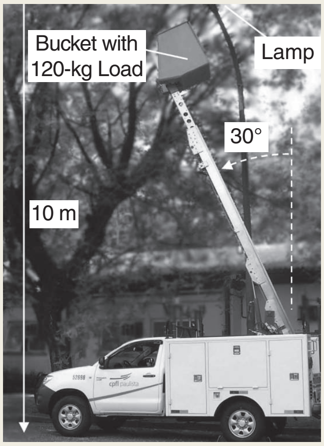
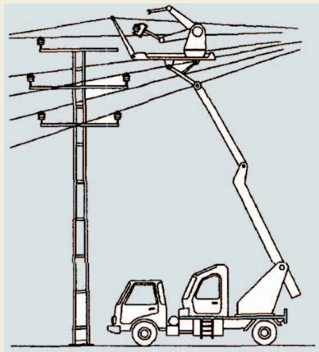
Ground robots have been used to perform maintenance work since 1980. Teleoperators for Operations, Maintenance, and Construction using Advanced Technology is an early prototype based on this technology, which was developed by the EPRI in 1986. The purpose of introducing this system was to address live-line procedures, mainly maintenance for high-voltage overhead transmission lines (138–765 kV) [9].

Four years later, in Japan, the Kyushu Electric Power Company introduced Phase I, which consisted of a robotic arm coupled to a ground vehicle. It needed a skilled operator for the use of the robotic arm and two operators for the control of the vehicle; the main weakness was the potential risk of human falls [74]. At the end of 1996, Kansai Electric Power Company updated the system to Phase II, which allowed live-line work. Phase II was designed for semiautomatic operations, with the operator assisting via remote controls from a cabin on the ground. The tasks were conducted automatically, with the operator providing judgment and commands for each unit task. The robotic system was composed of a dual-arm manipulator, cameras, a three-dimensional position-finding sensor, an automatic tool changer, an automatic material changer, and a third arm [75]. Publications from 2001 reported that roughly 93 robots from Phase I and Phase II were in use. The same year, the company presented a new update of this robot, called Phase III, which is fully autonomous [74].

In Spain, the Universidad Politécnica de Madrid introduced a maintenance robot intended to perform maintenance and repair of distribution lines rated up to 49 kV. The technology behind this system, called ROBTET, is reported in [76]. The main tasks of the robot were insulator-string replacement, opening and closing bridges, bypasses, and branch installation. The robot is composed of a truck, an insulated telescopic boom achieving a maximum height of 15 m, a rotating platform located on the top of the boom, two hydraulic manipulators with force reflection, a jib placed next to the slave manipulators on the rotating platform, and visual sensors (a stereovision system and an overall view camera) for control and surveillance of the robotic system by an operator.

Shanghai Jiaotong University developed a live-line robot called DWR-I

TABLE 3 — EXAMPLES OF UGVs USED IN POWER SYSTEMS [44], [81], [76].

TYPE OF ROBOT	EXAMPLES OF UGVS		
Name	LineMaster (three-phase)	Elevator IV	ROBTET
Research group	Quanta Energized Service	CPFL	Universidad Politécnica de Madrid
Year	2008	2014	1995
Inspection sensor	• Position control sensor • Visual camera	• Position control sensor to monitor bucket position • Visual camera	• Stereo vision system • Overall visual camera
Maintenance actuator	• Unit consists of adaptor, robotic arm, and fiberglass segment	• Telescopic column made of aluminum	• Two commercial master–slave system with force resection • Two slaves are hydraulically powered
Weight	136–1,020 kg per phase	1,500 kg	120 kg
Live-line working	Yes	Yes	Yes
Voltage level	Up to 345 kV	Distribution lines	Up to 56 kV
Energy source	Generator	Batteries or vehicle engine	Generator of 10 kW
Isolation	Electric	Electric	Electric
Autonomy	Controlled by a user in a vehicle or a lineman in a bucket	Controlled by a user in a bucket	The user sends and receives commands and information from the cabin on the truck
Height	60 m	10 m	15 m
Degrees of freedom	Three (elevation, inclination, and rotation)	Three (elevation, inclination, and rotation)	Six (master and slaves)
Main applications	Relocating energized conductors of different voltage levels	Development of maintenance process for street lights	Performing maintenance tasks on distribution networks
Platform			

CPFL: Companhia Paulista de Forca e Luz.

[77], intended to help the operator with the repair and maintenance of distribution live lines. The system is designed to work in distribution networks at medium voltage levels (up to 10 kV). The main tasks of the robot are exchanging broken insulators, exchanging fused switches, and cutting and jointing wires. The system reduces the human operators' workload and the human live-working risk, and it is composed of a mobile vehicle, booms, robot portions, and a control system.

Quanta Energized Services presented the LineMaster robotic arm [78], [79] as a solution for specific live-line projects, such as the replacement of rotten poles by utilizing the existing hole, the reconductoring of existing transmission lines conductors, and reframing and reinsulating of structures, all of which are typically difficult to execute with traditional live-line tools like hot sticks [44]. Currently, Quanta Energized Services manufactures, applies, and markets its robotics technology in two different systems: the single-phase and the three-phase LineMaster robotic arm. The single-phase LineMaster robotic arm is capable of handling voltages of up to 765 kV, supporting 4,535 kg in vertical and horizontal applications. The three-phase LineMaster robotic arm is capable of handling voltages of up to 345 kV per phase and supporting 136–1,020 kg per phase in vertical and horizontal applications, respectively [23].

Companhia Paulista de Forca e Luz, in partnership with Escola Politecnica of Sao Paulo University, reported the design of a robotic platform for maintenance of public lightning equipment in Brazil. The first and second versions of the system, called *Elevator*, are described in [80]. Elevator I was an electrically assisted automatic elevator used to reduce efforts in street light maintenance. The actualization of the robotic system Elevator II and Elevator III are intended to provide a wider workspace, enabling electricians to reach more components of the distribution line [81].

Meijo University, in collaboration with Chubu Electric Power Company in Japan, reported a semiautonomous system for checking the status of power lines. The performance of the proposed robot system was previously analyzed in a computer graphics simulator, which accounts for all the necessary technical specifications needed to solve different simulated cases. The controller is composed of a human–machine interface, a task planner, a motion planner, an arm controller, a tool controller, and a computer graphics display. The system is fitted with a robotic arm (from Mitsubishi Electric) and the three cameras (type SONY EVI-D100) for solving maintenance tasks in distribution lines such as installing a switchgear, removing the high-voltage insulator, and peeling the coating off a cable [82].

Different kinds of robots were developed for trimming branches and limbs from standing trees along rural power lines. A mobile robot called the *Tree Trimmer Telescopic* was patented in 2011 [83]. The mechanism was designed with the purpose of removing difficult-to-reach overhead tree branches. It consists of a motorized vehicle with a cab for the operator and an articulated boom. The end of the boom is equipped with a circular saw; by pivoting the boom sections vertically relative to the vehicle, the operator can cut a swath of branches or limbs. A tree-trimming apparatus mounted on a mobile support vehicle was patented in 2014 [84]. Similar devices to trim vertical sections of trees can be found in [85], and commercial prototypes are provided by TERRATECH [19]. A summary of the most relevant ground-based robots, including technical characteristics and main applications, is presented in Table 3.

UAVs

Helicopters are significant and efficient tools to accomplish inspection and maintenance work in power systems; they allow work on energized lines without interrupting service. The first work of this kind dates back to 1980; the essential idea was to replace the spacers in transmission systems [4]. Inspection work is conducted by a trained pilot, who is highly qualified to fly around power lines. A lineman in a special suit hangs from the helicopter while correcting and repairing damaged power lines [5].

Modern sensor technology, such as ultraviolet and infrared cameras, makes helicopters much better from an innovation point of view. The infrared cameras mounted in aerial vehicles enable pilots to detect damage by measuring temperature increases on electrical devices. The ultraviolet camera enables the detection of distance corona discharge, and the video camera enables visual inspection and damage detection along power lines [86]. Helicopters can be equipped with different actuators to maintain power lines, such as airborne tree trimming apparatuses [87], stringing blocks for building the transmission line, or hoses for cleaning insulator strings [4]. Because of the success of helicopters, UAV technology could appear to be a versatile and cost-effective solution for maintenance work in power systems. However, UAVs are not used for maintaining power systems due to the difficulty of installing mechanisms (e.g., robotic arms, clamps, and wrenches) for repairing the electrical equipment and their weight limitations. Instead, UAVs are mainly used for assisting ground operators, not for performing maintenance work [88].

Conclusions

This work presents the importance of robotic platforms in power systems through the review and analysis of current robotic technology uses. In particular, we examined inspection and maintenance tasks, for which brachiating robots, UGVs, and UAVs (not necessarily autonomous) have been shown to be the most used robotic platforms. However, despite the fact that robots can work in hostile environments (power plants are considered as hostile due to the risks to human life) and can replace a human labor force for a more efficient task execution, robots are still limited in their assignments. Most robots in power systems are designed and built for a single specific task, such as transmission-line supervision, detection of hot spots, or surveillance, thus limiting their potential in the industry. Future work in this field might focus on increasing the versatility of robots in power systems and improving their sensory systems to allow multitasking. In addition, increasing the interaction between robots and power systems beyond inspection and maintenance would be a step toward a fully autonomous power system industry.

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References

[1] Central Energia. (2011). Apagón en el sistema interconectado central. [Online]. Available: http://www.centralenergia.cl/2011/10/19/apagon-en-el-sistema-interconectado-central accessed 30-September-2015.

[2] C. De Michelis, C. Rinaldi, C. Sampietri, and R. Vario, "Condition Monitoring and Assessment of Power Plant Components," in *Power Plant Life Management and Performance Improvement*, John E. Oakey, Ed. Cambridge, U.K.: Woodhead Publishing, 2011, pp. 38–109.

[3] R. S. Goncalves and J. C. Mendes, "Review and latest trends in mobile robots used on power transmission lines," *Int. J. Adv. Robotic Syst.*, vol. 10, no. 12, pp. 1–14, Dec. 2013.

[4] E. Csanyi. (2013). Guidelines for the construction and maintenance of transmission lines. [Online]. Available: http://electrical-engineering-portal.com/guidelines-for-the-construction-and-maintenance-of-transmission-lines

[5] E. Head. (2015). High-value cargos. [Online]. Available: https://www.verticalmag.com/features/highvaluecargo/

[6] B. Wang, R. Guo, B. Li, L. Han, Y. Sun, and M. Wang, "SmartGuard: An autonomous robotic system for inspecting substation equipment," *J. Field Robotics*, vol. 29, no. 1, pp. 123–137, Jan./Feb. 2012.

[7] N. Pouliot and S. Montambault, "Field-oriented developments for LineScout Technology and its deployment on large water crossing transmission lines," *J. Field Robotics*, vol. 29, no. 1, pp. 25–46, Jan./Feb. 2012

[8] G. Caprari, A. Breitenmoser, W. Fischer, C. Hürzeler, F. Tâche, R. Siegwart, O. Nguyen, R. Moser, P. Schoeneich, and F. Mondada, "Highly compact robots for inspection of power plants," *J. Field Robotics*, vol. 29, no. 1, pp. 47–68, Jan./Feb. 2012.

[9] C. A. Veerappan, P. R. Green, and S. M. Rowland, "Visual live-line condition monitoring of composite insulators," in *Proc. 1st Int. Conf. Applied Robotics Power Industry*, 2010, pp. 1–6.

[10] L. C. Siebert, L. F. R. B. Toledo, P. A. B. Block, D. B. Bahlke, R. A. Roncolatto, and D. P. Cerqueira, "A survey of applied robotics for tree pruning near overhead power lines," in *Proc. 2014 3rd Int. Conf. Applied Robotics Power Industry*, 2014, pp. 1–5.

[11] J. Katrasnik, F. Pernus, and B. Likar, "A survey of mobile robots for distribution power line inspection," *IEEE Trans. Power Del.*, vol. 25, no. 1, pp. 485–493, Jan. 2010.

[12] J.-F. Allan and J. Beaudry, "Robotic systems applied to power substations—A state-of-the-art survey," in *Proc. 3rd Int. Conf. Applied Robotics Power Industry*, Oct. 2014, pp. 1–6.

[13] Y. Perrot, L. Gargiulo, M. Houry, N. Kammerer, D. Keller, Y. Measson, G. Piolain, and A. Verney, "Long-reach articulated robots for inspection and mini-invasive interventions in hazardous environments: Recent robotics research, qualification testing, and tool developments," *J. Field Robotics*, vol. 29, no. 1, pp. 175–185, Jan./Feb. 2012.

[14] B. Hazel, J. Côté, Y. Laroche, and P. Mongenot, "A portable, multiprocess, track-based robot for in situ work on hydropower equipment," *J. Field Robotics*, vol. 29, no. 1, pp. 69–101, Jan./Feb. 2012.

[15] S. Omari, P. Gohl, M. Burri, M. Achtelik, and R. Siegwart, "Visual industrial inspection using aerial robots," in *Proc. 3rd Int. Conf. Applied Robotics Power Industry*, Oct. 2014, pp. 1–5.

[16] I. Maurtua, L. Susperregi, A. Fernández, C. Tubío, C. Perez, J. Rodríguez, T. Felsch, and M. Ghrissi, "MAINBOT—mobile robots for inspection and maintenance in extensive industrial plants," *Energ. Procedia*, vol. 49, pp. 1810–1819, June 2014.

[17] K. Isawa, S. Nakayama, M. Ikeda, S. Takagi, S. Tosaka, and N. Kasai, "Robotic 3D SQUID imaging system for practical nondestructive evaluation applications," *Physica C*, vol. 432, no. 3–4, pp. 182–192, Nov. 2005.

[18] A. Nayak and S. K. Pradhan, "Design of a new in-pipe inspection robot," *Procedia Eng.*, vol. 97, pp. 2081–2091, Dec. 2014.

[19] TerraTech. (2016). Integrated tree trimming systems. [Online]. Available: http://www.terratechmfg.com

[20] MIR Innovation. (2016). LineROVer—A compact robot for inspecting overhead lines. [Online]. Available: http://mir-innovation.hydroquebec.com/mir-innovation/en/transmission-solutions-linerover.html

[21] MIR Innovation. (2016). LineROVer—A versatile robot for inspecting overhead lines. [Online]. Available: http://mir-innovation.hydroquebec.com/mir-innovation/en/transmission-solutions-linescout.html

[22] HIBOT CORP. (2016). Expliner—Robot for power line inspection. [Online]. Available: https://www.hibot.co.jp

[23] Quanta Services. (2016). Quanta energized service. [Online]. Available: http://www.quantaenergized.com/

[24] Hexagon Geosystems. (2016). Aibotix. [Online]. Available: https://www.aibotix.com/

[25] D. P. Kothari and I. J. Nagrath, *Modern Power System Analysis*. New Delhi, India: Tata McGraw Hill, 2009.

[26] L. Grigsby, *Electric Power Engineering Handbook*. New York: Taylor & Francis, 2016.

[27] H. Cunha Furtado and I. Le May, "High temperature degradation in power plants and refineries," *Mater. Res.*, vol. 7, no. 1, pp. 103–110, Mar. 2004.

[28] M. Shawal Jadin and S. Taib, "Recent progress in diagnosing the reliability of electrical equipment by using infrared thermography," *Infrared Phys. Techn.*, vol. 55, no. 4, pp. 236–245, July 2012.

[29] J.-Y. Park, J.-K. Lee, B.-H. Cho, and K.-Y. Oh, "An inspection robot for live-line suspension insulator strings in 345-kV power lines," *IEEE Trans. Power Del.*, vol. 27, no. 2, pp. 632–639, Apr. 2012.

[30] H. Zhang, Y. He, B. Gao, G. Y. Tian, L. Xu, and R. Wu, "Evaluation of atmospheric corrosion on coated steel using k-band sweep frequency microwave imaging," *IEEE Sensors J.*, vol. 16, no. 9, pp. 3025–3033, May 2016.

[31] C. H. Liu, J. Chen, Y. X. Lai, D. H. Zhu, Y. Gu, and J. H. Chen, "Enhancing electrical conductivity and strength in al alloys by modification of conventional thermo-mechanical process," *Mater. Design*, vol. 87, pp. 1–5, Dec. 2015.

[32] S. Refsnæs, N. Magnusson, and T. Ulleberg, "Laboratory corrosion tests on overhead line conductors with bird protection systems," *Int. Trans. Elect. Energy Syst.*, vol. 24, no. 8, pp. 1185–1191, Aug. 2014.

[33] S. Montambault and N. Pouliot, "The HQ linerover: contributing to innovation in transmission line maintenance," in *Proc. IEEE 10th Int. Conf. Transmission Distribution Construction Operation Live-Line Maintenance*, Apr. 2003, pp. 33–40.

[34] F. Zhang, L. Cao, R. Guo, L. Zhong, J. Jia, Y. Jia, and X. Chi, "Extended applications of linerover technology," in *Proc. 10th IEEE Int. Conf. Control Automation*, June 2013, pp. 1415–1418.

[35] N. Pouliot, P. L. Richard, and S. Montambault, "LineScout Technology opens the way to robotic inspection and maintenance of high-voltage power lines," *IEEE Power Energy Technol. Syst. J.*, vol. 2, no. 1, pp. 1–11, Mar. 2015.

[36] N. Pouliot and S. Montambault, "LineScout Technology: from inspection to robotic maintenance on live transmission power lines," in *Proc. IEEE Int. Conf. Robotics Automation*, May 2009, pp. 1034–1040.
[37] N. Pouliot, P. Richard, and S. Montambault, "LineScout power line robot: characterization of a UTM-30LX LIDAR system for obstacle detection," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots Systems*, Oct 2012, pp. 4327–4334.
[38] P.-L. Richard, N. Pouliot, and S. Montambault, "Introduction of a LIDAR-based obstacle detection system on the LineScout power line robot," in *Proc. IEEE/ASME Int. Conf. Advanced Intelligent Mechatronics*, July 2014, pp. 1734–1740.
[39] P. Debenest and M. Guarnieri, "Expliner x2014: From prototype towards a practical robot for inspection of high-voltage lines," in *Proc. 1st Int. Conf. Applied Robotics Power Industry*, Oct 2010, pp. 1–6.
[40] G. Rui, Z. Feng, C. Lei, and Y. Jun, "A mobile robot for inspection of overhead transmission lines," in *Proc. 3rd Int. Conf. Applied Robotics Power Industry*, Oct. 2014, pp. 1–3.
[41] L. Zheng and Y. Ruan, "Autonomous inspection robot for power transmission lines maintenance while operating on the overhead ground wires," *Int. J. Adv. Robotic Syst.*, vol. 7, no. 4, pp. 107–112, Dec. 2010.
[42] A. J. Phillips, J. M. Major, and G. R. Bartlett, "Line inspection robot and system," U.S. Patent 8,666,553 B2, March 4, 2014.
[43] D. Elizondo, T. Gentile, H. Candia, and G. Bell, "Overview of robotic applications for energized transmission line work; technologies, field projects and future developments," in *Proc. 1st Int. Conf. Applied Robotics Power Industry*, Oct. 2010, pp. 1–7.
[44] D. Elizondo, T. Gentile, H. Candia, and G. Bell, "Ground based robots for energized transmission line work-technology description, field projects and technical-economical justification of their application," in *Proc. 2010 IEEE/PES Transmission Distribution Conf. Exposition Latin America*, Nov. 2010, pp. 700–705.
[45] R. Guo, B. Li, Y. Sun, and L. Han, "A patrol robot for electric power substation," in *Proc. ICMA 2009 Int. Conf. Mechatronics Automation*, Aug. 2009, pp. 55–59.
[46] J. Wang and W. Chen, "A novel localization system based on infrared vision for outdoor mobile robot," in *Proc. 2010 Int. Conf. Life System Modeling Simulation Intelligent Computing Int. Conf. Intelligent Computing Sustainable Energy Environment Part III*, Berlin, Heidelberg, 2010, pp. 33–41.
[47] H. Wu, Y. Wu, C. Liu, and G. Yang, "Visual data driven approach for metric localization in substation," *Chinese J. Electron.*, vol. 24, no. 4, pp. 795–801, Oct. 2015.
[48] P. Xiao, M. Fu, H. Wang, T. Wang, C. Zhang, and Y. Li, "Design of a 2D laser mapping system for substation inspection robot," in *Proc. 4th Int. Conf. Applied Robotics Power Industry*, Oct. 2016, pp. 1–5.
[49] I. Purkayastha, M. Tirozzi, J. Smith, and K. Monti, "Mobile inspection robot," U.S. Patent 13,766,125, Sept. 5, 2013.
[50] Z. Xueheng, "The substation inspection robot," Chinese Patent 201,610,570,004, Oct. 12, 2016.
[51] S. Antunes and K. Bousson, "Safe flight envelope for overhead line inspection," in *Proc. 3rd Int. Conf. Applied Robotics Power Industry*, Oct. 2014, pp. 1–6.
[52] J.-J. Xiong and E.-H. Zheng, "Position and attitude tracking control for a quadrotor UAV," *ISA Trans.*, vol. 53, no. 3, pp. 725– 731, May 2014.
[53] W. de Britto Vidal Filho and A.M. de Almeida Pinto, "VTOL aerial robot for inspection of transmission line," in *Proc. 3rd Int. Conf. Applied Robotics Power Industry*, Oct. 2014, pp. 1–4.
[54] Z. Li, T. S. Bruggemann, J. J. Ford, L. Mejias, and Y. Liu, "Toward automated power line corridor monitoring using advanced aircraft control and multisource feature fusion," *J. Field Robotics*, vol. 29, no. 1, Jan./Feb. 2012, pp. 4–24.
[55] J. T. F. B. de Sousa, B. C. Pinheiro, and U. F. Moreno, "Unmanned vehicles network: Platforms and software toolchain," in *Proc. 3rd Int. Conf. Applied Robotics Power Industry*, Oct. 2014, pp. 1–6.
[56] S. Pirbodaghi, D. Thangarajan, T. H. Liang, M. Shanmugavel, V. Ragavan, and J. S. Sequeira, "A cooperative heterogeneous unmanned autonomous systems solution for monitoring and inspecting power distribution system," in *Proc. Int. Conf. Control Instrumentation Communication Computational Technologies*, Dec. 2015, pp. 495–502.
[57] Q. Wu and J. An, "An active contour model based on texture distribution for extracting inhomogeneous insulators from aerial images," *IEEE Trans. Geosci. Remote Sens.*, vol. 52, no. 6, June 2014, pp. 3613–3626.
[58] J. Zhang, H. Shan, X. Cao, P. Yan, and X. Li, "Pylon line spatial correlation assisted transmission line detection," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 50, no. 4, pp. 2890–2905, Oct. 2014.
[59] H. Sharma, R. Bhujade, V. Adithya, and P. Balamuralidhar, "Vision-based detection of power distribution lines in complex remote surroundings," in *Proc. Twentieth Nat. Conf. Communications*, Feb. 2014, pp. 1–6.
[60] Z. Li, Y. Liu, R. Walker, R. Hayward, and J. Zhang, "Towards automatic power line detection for a UAV surveillance system using pulse coupled neural filter and an improved Hough transform," *Mach. Vision Appl.*, vol. 21, no. 5, pp. 677–686, Aug. 2010.
[61] G. Zhou and X. Zhou, "Seamless fusion of LIDAR and aerial imagery for building extraction," *IEEE Trans. Geosci. Remote Sens.*, vol. 52, no. 11, pp. 7393–7407, Nov. 2014.
[62] S. J. Mills, M. P. Gerardo Castro, Z. Li, J. Cai, R. Hayward, L. Mejias, and R. A. Walker, "Evaluation of aerial remote sensing techniques for vegetation management in power-line corridors," *IEEE Trans. Geosci. Remote Sens.*, vol. 48, no. 9, pp. 3379–3390, Sept. 2010.
[63] M. Simic, C. Bil, and V. Vojisavljevic, "Investigation in wireless power transmission for UAV charging," *Procedia Comput. Sci.*, vol. 60, pp. 1846–1855, Sept. 2015.
[64] M. Yang, Z. Liang, H. Qian, E. Li, and G. Yang, "Design and analysis of multi-winding power current transformer for power transmission lines inspection robot," *Procedia Eng.*, vol. 29, pp. 2187– 2193, Feb. 2012.
[65] I. Golightly and D. Jones, "Visual control of an unmanned aerial vehicle for power line inspection," in *Proc. 12th Int. Conf. Advanced Robotics*, July 2005, pp. 288–295.
[66] D. I. Jones, "An experimental power pick-up mechanism for an electrically driven UAV," in *Proc. IEEE Int. Symp. Industrial Electronics*, June 2007, pp. 2033–2038.
[67] K. Toussaint, N. Pouliot, and S. Montambault, "Transmission line maintenance robots capable of crossing obstacles: State-of-the-art review and challenges ahead," *J. Field Robotics*, vol. 26, no. 5, pp. 477–499, 2009.
[68] M. Campos, G. Pereira, S. Vale, A. Bracarense, G. Pinheiro, and M. Oliveira, "A mobile manipulator for installation and removal of aircraft warning spheres on aerial power transmission lines," in *Proc. IEEE Int. Conf. Robotics Automation*, 2002, vol. 4, pages 3559–3564.
[69] B.-H. Cho, S.-H. Byun, J.-Y. Park, and J.-S. Kim, "Development of automatic inspection robot for live-line insulators," in *Proc. IEEE 11th Int. Conf. Transmission Distribution Construction Operation Live-Line Maintenance*, Oct. 2006, pp. 1–5.
[70] J.-Y. Park, J.-K. Lee, B.-H. Cho, and K.-Y. Oh, "Robot mechanism for inspection of live-line suspension insulator string," U.S. Patent 12,254,014, Aug. 2012.
[71] J.-F. Allan, S. Lavoie, S. Reiher, and G. Lambert, "Climbing and pole line hardware installation robot for construction of distribution lines," in *Proc. 1st Int. Conf. Applied Robotics Power Industry*, Oct. 2010, pp. 1–5.
[72] M. N. Ahmadabadi, H. Moradi, A. Sadeghi, A. Madani, and M. Farahnak, "The evolution of UT pole climbing robots," in *Proc. 1st Int. Conf. Applied Robotics Power Industry*, Oct. 2010, pp. 1–6.
[73] D. Schmidt and K. Berns, "Climbing robots for maintenance and inspections of vertical structures—a survey of design aspects and technologies," *Robotics Auton. Syst.*, vol. 61, no. 12, pp. 1288–1305, Dec. 2013.
[74] V. Banthia, Y. Maddahi, S. Balakrishnan, and N. Sepehri, "Haptic-enabled teleoperation of base-excited hydraulic manipulators applied to live-line maintenance," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots Systems*, Sept. 2014, pp. 1222–1229.
[75] K. Takaoka, K. Yokoyama, H. Wakisako, K. Yano, K. Higashijima, and S. Murakami, "Development of the fully-automatic live-line maintenance robot-phase III," in *Proc. IEEE Int. Symp. Assembly Task Planning*, May 2001, pp. 423–428.
[76] L. F. Penin, R. Aracil, M. Ferre, E. Pinto, M. Hernando, and A. Barrientos, "Telerobotic system for live power lines maintenance: ROBTET," in *Proc IEEE Int. Conf. Robotics and Automation*, May 1998, vol. 3, pp. 2110–2115.
[77] L. Shouyin, L. Yanping, and Q. Wei, "Robotic live-working for electric power lines maintenances," in *Proc. 4th IEEE Conf. Industrial Electronics Applications*, May 2009, pp. 1716–1719.
[78] C. W. Devine and D. N. O'Connell, "Boom mountable robotic arm," U.S. Patent 8,684,333, Apr. 1, 2014.
[79] D. N. O'Connell, and D. K. Wabnegger, "Method for stringing replacement optical ground wire or static wire near energized power lines," U.S. Patent App. 20150249325 A1, Sept. 3 2015.
[80] R. A. Roncolatto, N. W. Romanelli, A. Hirakawa, O. Horikawa, D. M. Vieira, R. Yamamoto, and V. C. Finotto, "Robotics applied for safety improvement in the power distribution lines maintenance," in *Proc. IEEE/PES Transmission Distribution Conf. Exposition*, Apr. 2008, pages 1–7.
[81] W. Scaff, R. A. Pavani, A. Riyuiti Hirakawa, O. Horikawa, and A. Chamas Filho, "Automatic elevator for assisting maintenance of distribution power line control system," in *Proc. 3rd Int. Conf. Applied Robotics Power Industry*, Oct. 2014, pp. 1–6.
[82] K. Tsukahara, Y. Tanaka, Y. He, T. Miyamoto, and K. Tatsuno, "Conceptual Design of a Power Distribution Line Maintenance Robot Using a Developed CG Simulator and Experimental Robot System," in *Proc. First Int. Conf. Simulation Modeling Programming Autonomous Robots,* Venice, Italy, 2008, pp. 340–351.
[83] J. L. Robitaille, "Tree trimmer telescopic," U.S. Patent 20110048579 A1. Mar. 3, 2011.
[84] J. Prohaska, "Mobile tree-trimming apparatus," U.S. Patent 13,819,844. Apr. 10, 2014.
[85] C. Skipper and J. Kregl, "Rotary plant hedger," U.S. Patent 13,833,536. May 8, 2014.
[86] OFIL Systems. (2013). aviROM: A flying corona detection robot system. [Online]. Available: http://www.ofilsystems.com/catalog/index.html
[87] A. Haddock and D. Haddock, "Apparatus and method for aerial chemical trimming of vegetation," U.S. Patent 9,192,947, Nov. 24 2015.
[88] M. Nayyerloo, X. Chen, W. Wang, and J. G. Chase. (2009). Cable-Climbing Robots for Power Transmission Lines Inspection. *Mobile Robots—State of the Art in Land, Sea, Air, and Collaborative Missions*. [Online]. Available: https://www.intechopen.com/books/mobile-robots-state-of-the-art-in-land-sea-air-and-collaborative-missions/cable-climbing-robots-for-power-transmission-lines-inspection