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Cable-Climbing Robots for Power Transmission Lines Inspection

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1. Introduction

Power transmission line inspection is of utmost importance for power companies towards having sustainable electricity supply to vast number of customers in major industries as well as households in a city. Inspection provides valuable data from status of the line, thus helps line engineers to plan for necessary repair or replacement works before any major damages which may result in outage.

Constant energy supply to the customers requires performing all the inspection tasks without de-energizing the line, so live line inspection methods are of the most interest to power companies. These companies perform patrol inspection mainly using helicopters equipped with infrared and corona cameras to detect observable physical damages as well as some internal deterioration to the line and line equipment. However, aerial inspection is costly and always there is a risk of contact with live lines and loss of life. Moreover, there are some critical specifications of the line such as internal corrosion of steel reinforced aluminium conductors that should be inspected precisely from close distances to the line that are not accessible by a mobile platform such as a helicopter or even an unmanned aerial vehicle (UAV). Hence, power companies have endeavored to make especial cable-climbing robots to accomplish inspection tasks from close distances to the hot line.

Thanks to technological advances, utilizing robots as reliable substitutes for human beings in hazardous environments such as live lines has become possible. For many tasks requiring high precision over a long period of time, robots even do their job better than human operators. However, power companies have mainly focused on automating inspection tasks more willingly than making autonomous systems to perform repair works on the live line due to the fact that repair works are often complex to be accomplished by a robot.

In the past two decades, researchers have endeavored to make fully autonomous and intelligent cable-climbing robots equipped with necessary sensors for hot line inspection, aiming at making a cable-climbing mechanism with obstacle avoidance capability to pass the line equipment and the tower. Also some research has been done to devise a durable power supply method for the hot line inspection robots to make them sufficiently durable to perform inspection over long distances of live lines without interruptions for recharging the power source. Inspection data quality enhancement has been another challenging issue in this field due to the fact that swinging of the inspection robot in windy climates and even sometimes during the navigation makes the captured images of the line, as the main inspection data for line status evaluation, blurry. These undesirable vibrations also make some problems in the robot's navigation, which mainly relies on a vision system, in most of the proposed designs.

The robot's mechanical mechanism as main part of the robot design may significantly affect other issues in the whole design process such as energy consumption and inspection data quality. Hence, this chapter aims to review some of the main efforts made over the past 20 years in cable-climbing mechanism design for power lines inspection to provide a basis for future designs and developments in this field.

The chapter has organized as follows. Section two of the chapter briefly reviews different kinds of faults, which may occur in power lines, and origins of these faults. In the third section, which is the main part of this chapter, the focus will be on reviewing different types of mechanisms proposed for navigation and obstacle avoidance on power lines, advantages and disadvantages of each proposed mechanism over others, and adaptability of these mechanisms to power line environment. We then conclude the chapter in the last section.

2. Problems of deterioration in transmission lines and their symptoms

Transmission lines are exposed to variety of factors, such as corrosion and wind induced vibrations, which cause different problems and limit life time of the lines. Damage to the transmission lines can be categorized into two main groups: damage to the insulators and damage to the conductors.

2.1 Damage to the insulators

The insulators are affected by impact, weathering, cyclic mechanical and thermal loading, electro-thermal causes, flexure and torsion, ionic motion, cement growth, and corrosion (Aggarwal et al., 2000). Temperature difference between hot sunny days and freezing cold nights as well as the heat generated by fault current arcs cause thermal cycling, which produce micro-cracks and allows water to penetrate into material. The amount of imposed stress depends on relative expansibility of dielectric, metal fittings, and the cement used to fix the metal fittings of the line to the dielectric.

Cement growth, which is mainly caused by delayed hydration of periclase (MgO) as well as sulphate related expansion, generates radial cracks in the porcelain insulators' shell and makes them faulty (Aggarwal et al., 2000). Contaminants in the atmosphere, such as sea or road salts, can attack both Portland cement itself, or if penetrate into metal parts, can corrode galvanizing surface. Ionic motion caused by electric field makes this situation worse.

2.2 Damage to the conductors

The steel reinforced aluminium conductors (ACSR) are one of the most popular conductor types. The most important phenomenon that degrades such conductors is corrosion of aluminium strands. Pollutants and moisture, in the form of aqueous solutions containing chloride ions, ingress into the interface between the steel and the aluminium strands and attack galvanizing protection of the steel. Corrosion of the galvanizing coat exposes steel and aluminium to each other and leads to galvanic corrosion between iron and aluminium. As an anode, aluminium corrodes rapidly and white powder aluminium hydroxide is produced. Loss of aluminium strands decreases current carrying capacity and mechanical strength of the line (Cormon Ltd, 1998; Aggarwal et al., 2000).

In addition to corrosion, wind induced vibrations can make severe mechanical damage to the conductors due to generating cyclic mechanical load. The wind flow creates vortices downstream when it passes the line. These vortices produce fluctuating lift and drag forces causing aeolian vibrations with frequencies from 10-30 Hz and amplitudes of the order of diameter of the conductor. In bundled conductors, the wind also induces sub-conductor oscillations, which can cause fretting of the aluminium strands near the clamps. The fretting reduces the fatigue strength of the line and speeds up the failure process.

2.3 Symptoms of the transmission line damage and detection methods

Damage to the line can be detected through investigation of their symptoms. Most of the line problems produce unusual partial discharges. Whenever the electric field intensity on the line surface exceeds the breakdown strength of air, electrons in the air around the conductor ionize the gas molecules and partial discharges, namely corona effects, occur. High frequency partial discharges produce radio noise in ultra-high frequency range, as well as audible noise in ultra-sonic range. In addition to noise, discharges send a current to the line. This current can also be used to detect faults. Depending on the weather, age of the line, problem conditions, and other factors, the level of discharge can also be different. Abnormal temperature is another symptom, which can be used to identify defects on the transmission lines.

Based on aforementioned major symptoms, following techniques are mainly used for detecting faults in the transmission lines (Aggarwal et al., 2000):

1. Ultrasonic detection
2. Measurement of corona pulse current inconsistency
3. Partial discharge detector
4. Infrared inspection of overhead transmission lines
5. Radio noise detection system
6. Solar-blind power line inspection system (through detecting UV)
7. Corona current monitor for high voltage power lines
8. Fiber optic application to transmission line inspection
9. Audible noise meters
10. Field testing of insulators

3. Cable-Climbing mechanisms for power line inspection

3.1 The design environment

Power lines are a dangerous environment with intensive electric and magnetic fields. Power lines are also a complex environment, and difficult for robots to navigate. The simplest power lines have one conductor per phase hung on insulator strings, which can be either suspension or strain insulators. Besides insulators, there are other obstacles on the conductors, such as dampers, aircraft warning lights, and clamps. In bundle power lines, which have more than one conductor per phase, there are even more obstacles such as spacers and spacer dampers (Figure 1)[1].

The robot travels suspended from the conductor and has to cross obstacles along the power line that requires complex robotic mechanisms including conductor grasping systems and robot driving mechanisms. Moreover, an obstacle detection and recognition system, robot control system, communication, inspection platform equipped with necessary sensors and measurement devices, power supply and electromagnetic shielding have to be considered in robot mechanism design and construction.

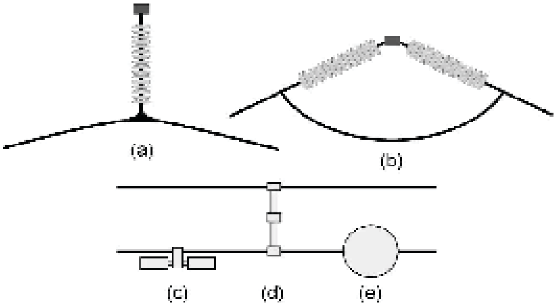

Fig. 1. Different obstacles on power line conductors: (a) suspension insulator, (b) strain insulator, (c) damper, (d) spacer/spacer damper (e) aircraft warning sphere (Katrasnik et al., 2008).

3.2 Cable-climbing mechanisms designed over the past 20 years

One of the first cable-climbing mechanisms presented in (Aoshima et al., 1989). The proposed mechanism, which was designed for telephone lines inspection, compared to its previous works is able to transfer to branch wires, and thus provides more flexibility in cable-climbing. The robot structure, as shown in Figure 2, consists of a multi-unit of six identical modules with three degrees of freedom: longitudinal movement on the cable, horizontal rotation about robot's longitudinal axis parallel to the power line, and vertical elongation of robot's arms.

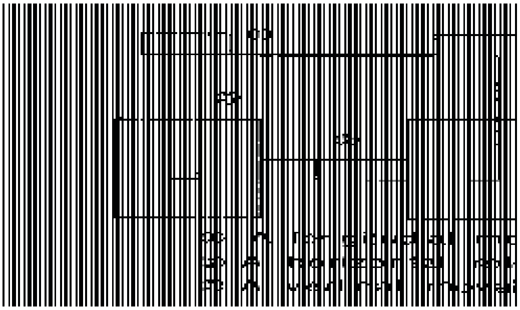

Fig. 2. Proposed cable-climbing mechanism in (Aoshima et. al., 1989).

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[1] All of the figures and tables used in this literature survey have been taken from the original works presented by their authors.

Using different configuration of these six units, the robot will be able to adapt itself to different geometrical environments and avoid obstacles with different shapes and sizes, transfer to a branch wire, and even transfer to a parallel line. As an example to show the flexibility of the proposed mechanism by Aoshima et al., Figure 3 describes how the robot transfers to a branch wire. The proposed robot has good maneuverability over different obstructions and variety of different geometrical environments on the power lines, but as Figure 3 shows, the robot is complex in control.

One of the first efforts towards designing a more simple cable-climbing mechanism carried out by (Sawada et al., 1991) to inspect fibre-optic overhead ground wires (OPGWs). The proposed robot, as shown in Figure 4, consists of a vehicle assembly to navigate on the power line, an arc shape guide rail, a guide rail manipulator, and a balancer with controller to pass the obstacles. It can travel on slopes of up to 30°. When the robot comes across an obstacle, it opens its rail and hangs it on the line on both sides of the obstacle. Then the drive mechanism detaches from the conductor and travels on the rail to the other side of the obstacle. Utilizing such an obstacle avoidance mechanism, the robot is able to negotiate towers as well and transfer to the next span to inspect rest of the power line.

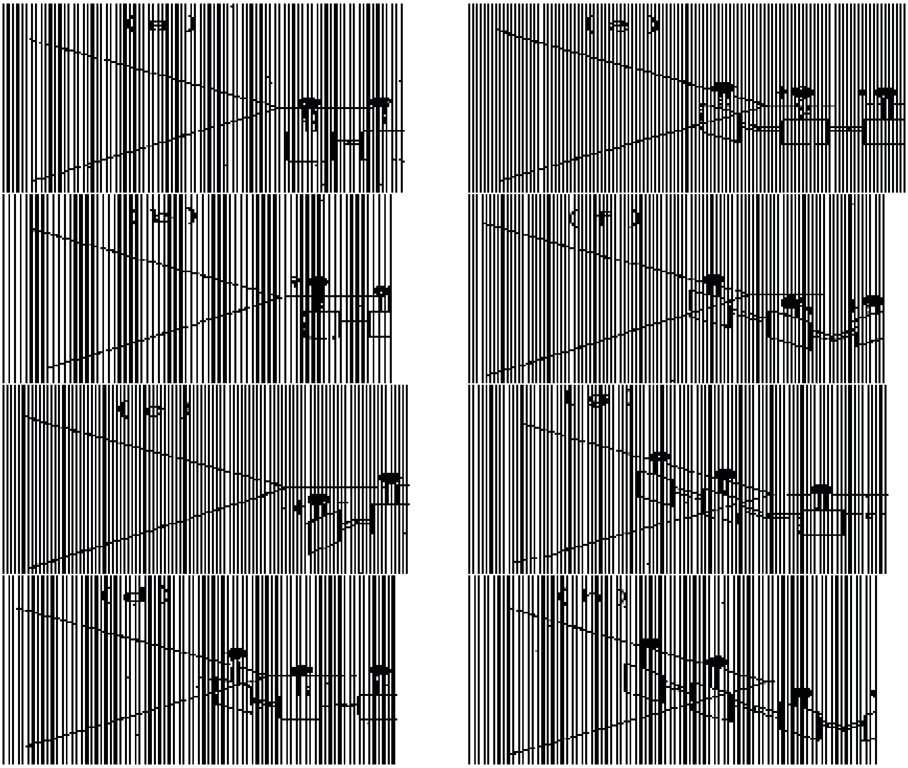


Fig. 3. How the multi-unit robot transfers to a branch wire (Aoshima et al., 1989)

The proposed robot did not have proper shielding for live line inspection and could not travel on phase conductors. Moreover, stability issues in windy climates and slow obstacle overcoming mechanism, for example, spending 15 minutes to overcome each tower, were unresolved issues in the proposed robot.

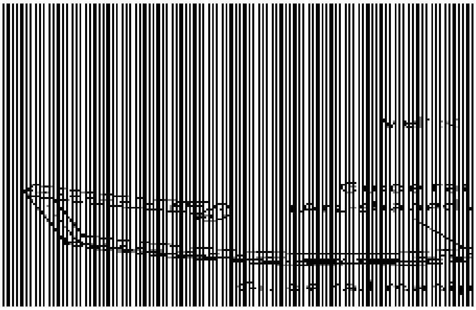


Fig. 4. Basic configuration of proposed mechanism in (Sawada et al., 1991)

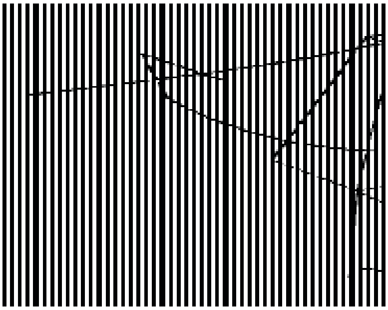


Fig. 5. How Sawada and his colleagues' robot passes the towers (Sawada et al., 1991).

In the same year, a project with same purpose was done by Higuchi et al. The proposed stride type robot, as shown in Figure 6, can move on a ground wire stretched on top of the towers and is also able to pass the towers (Higuchi et al., 1991). The robot can navigate on the overhead ground lines using two arms to take steps and a crawling mechanism to move on top of the towers (Figure 7).

The presented work has the stability problems in windy climates and is also more complex to control than the work in (Sawada et al. 1991). In addition, as Figs. 6 and 7 show, the design is specific for inspection of the overhead ground wires stretched on top of the towers with a flat area on top and cannot be used as a general inspection robot for all types of the power lines. For instance, the robot cannot pass the towers when it is traveling on phase conductors as the robot is not able to overcome the insulators.

To achieve both stability in movement and simplicity in control, another project ran by Tsujimura and Morimitsu in 1997 to make a cable-climbing robot for the telecommunication lines inspection. The proposed robot in (Tsujimura & Morimitsu, 1997) and the locomotion principle have been shown in Figs. 8 and 9. A linkage mechanism creates a gait kinematically and causes the arms to hang on the cable at intervals. The robot walks parallel to the cable and as it moves, due to the nature of the movements, can avoid obstacles as well.

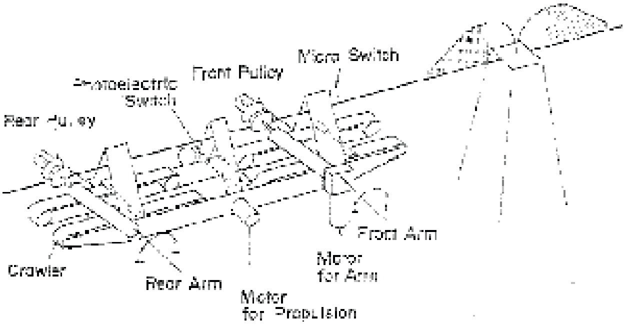


Fig. 6. Architecture of the robot proposed by (Higuchi et al., 1991)

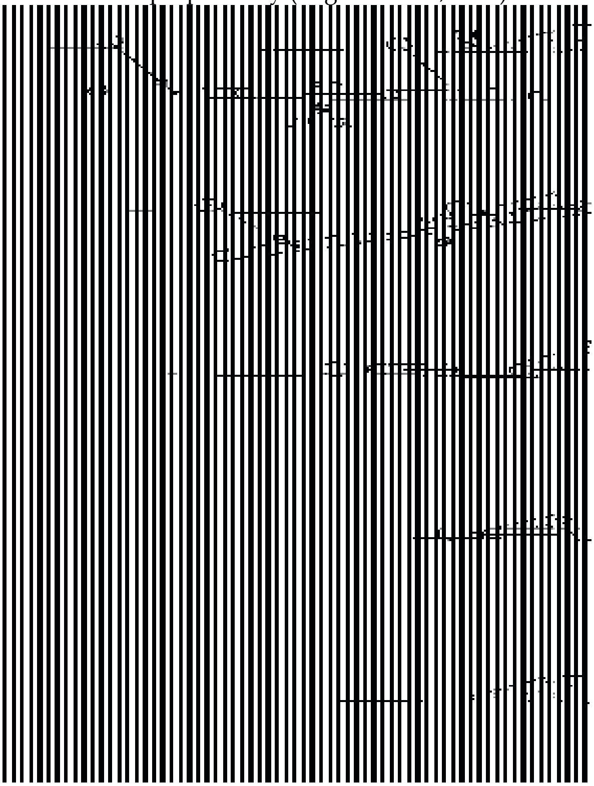


Fig. 7. Sequence of going over the tower in (Higuchi et al., 1991)

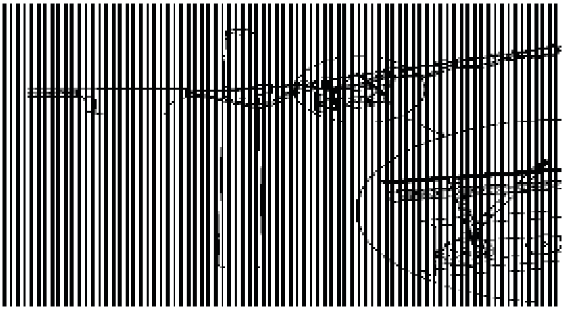
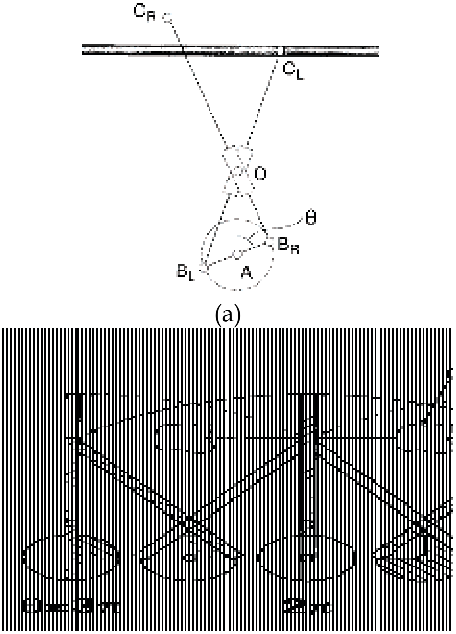


Fig. 8. Proposed cable-climbing mechanism in (Tsujimura & Morimitsu, 1997)

The proposed mechanism can provide constant moving speed, which is ideal for inspection, is simple to do, stable, and simple to control, but cannot transfer to the angled lines.



(a)

(b)

Fig. 9. Locomotion principle of the proposed mechanism in (Tsujimura & Morimitsu, 1997) (a) linkage that provides gait movement and (b) simulation of movements of one of the robot's arms

Meanwhile, some researchers focused on making fully operational robots to carry out special tasks on the power lines, even though they were not able to perform the task fully autonomously. One such robot was presented by Campos et al. in 2002. The proposed robot, shown in Figure 10, is a simple but operational cable-climbing mechanism for installation and removal of the aircraft warning spheres. This robot can only navigate on part of the line between two towers without avoiding any obstacle. Similar mechanisms, shown in Figs. 11

and 12, can be found in (Sato Ltd., 1993) and (Cormon Ltd, 1998), respectively. The proposed mechanisms consist of a trolley with two pulleys on top that can move the trolley and all the required manipulators and the inspection tools. The mechanisms proposed by Campos et al., Sato Ltd., and Cormon Ltd. have been tested in real working conditions and the two latter are commercially available. Although these robots are not able to pass the obstructions on the power lines or transfer to the next span, they are simple and operational.

Fig. 10. The aircraft warning sphere installation and removal mechanism proposed in (Campos et al., 2002)

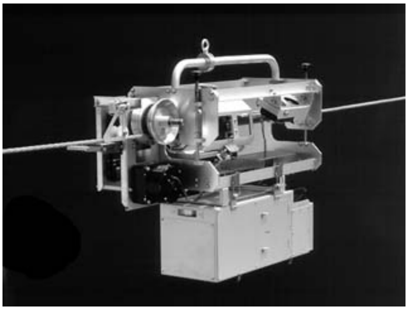


Fig. 11. Automatic overhead power transmission line damage detector developed by (Sato Ltd., 1993).

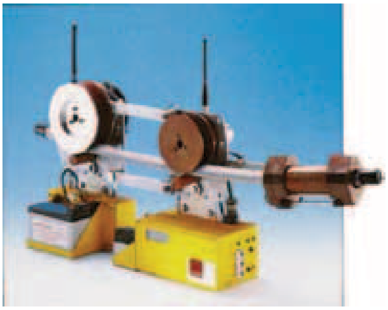


Fig. 12. Mobile corrosion detector proposed in (Cormon Ltd., 1998)

Some more throughput mechanisms were developed in 2004. One of these mechanisms has been shown in Figure 13. This figure shows a sketch of the mechanical mechanism designed by (Tang et al., 2004). The proposed robot has two front and rear arms and a body. There is a gripper on top of each arm and a running wheel on top of the body. In addition, using wheels in the gripper design have enabled this robot to move along the line back and forth even when the grippers grasp the line.

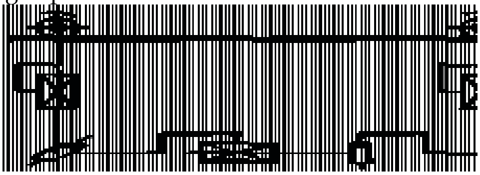


Fig. 13. Proposed mechanism by (Tang et al., 2004)

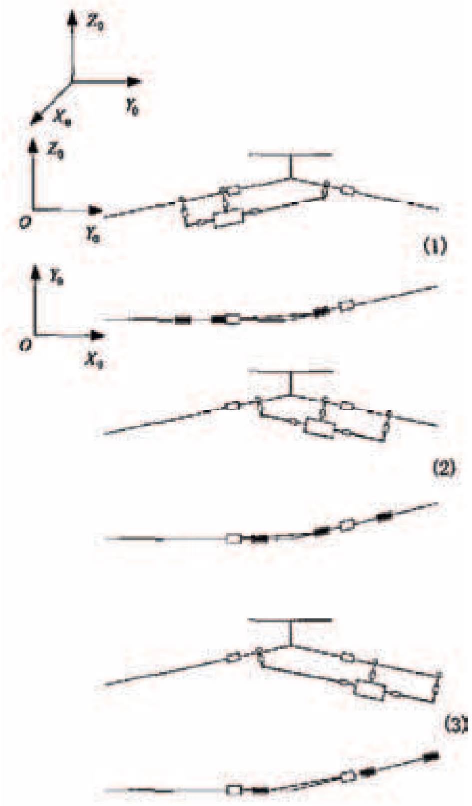


Fig. 14. Proposed obstacle navigation procedure in (Tang et al., 2004)

The obstacle navigation process is shown in Figure 14. When the robot detects an obstacle, the rear arm gripper grasps the line, and the front arm elongates to pass the obstruction. In the second step, the front arm gripper grasps the line, and the running wheels get off from the wire. Next, the two grippers continue to move forward, and consequently the body can move across the obstacle. Finally, the running wheel turns over the wire and grasps it, the rear arm gripper is detached from the line and pass the obstacle. Considering different distances between two consecutive obstacles and different tower sizes in mechanism design, the proposed robot can pass all types of the obstacles on straight lines autonomously.

Similar crawling mechanism also proposed by (Wolff et al., 2001), and modified by (Nayyerloo et al., 2007). In the latter, a mechanical mechanism, as shown in Figure 15, was proposed. The mechanism has three similar grippers mounted on top of three arms, which can go up and down. These three independent grippers make the robot able to be fixed to the line or move along the line easily when it is hung from the line. Two motors in the driving system mounted on top of the middle arm drive the whole robot. The front and rear arms can move along the robot length synchronously using the arm driving mechanism and two connection rods, which have connected these two arms together. The middle arm is fixed to the robot body.

The proposed arm driving mechanism plays two roles for the robot: translation of the front and rear arms along the robot length and translating the robot itself. The front and rear arms have been mounted on two nuts of a main screw, which represents the robot body. If the main screw is driven while the middle gripper has been clamped to the line, both movable arms will move along the line together. In a same way, there is another possibility to fix two movable arms to the line and drive the screw to move the robot body.

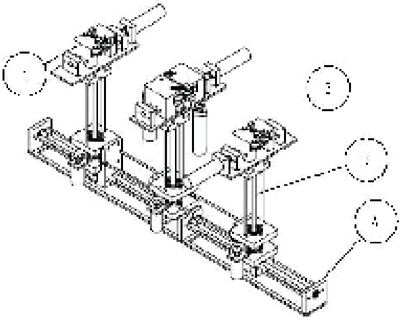
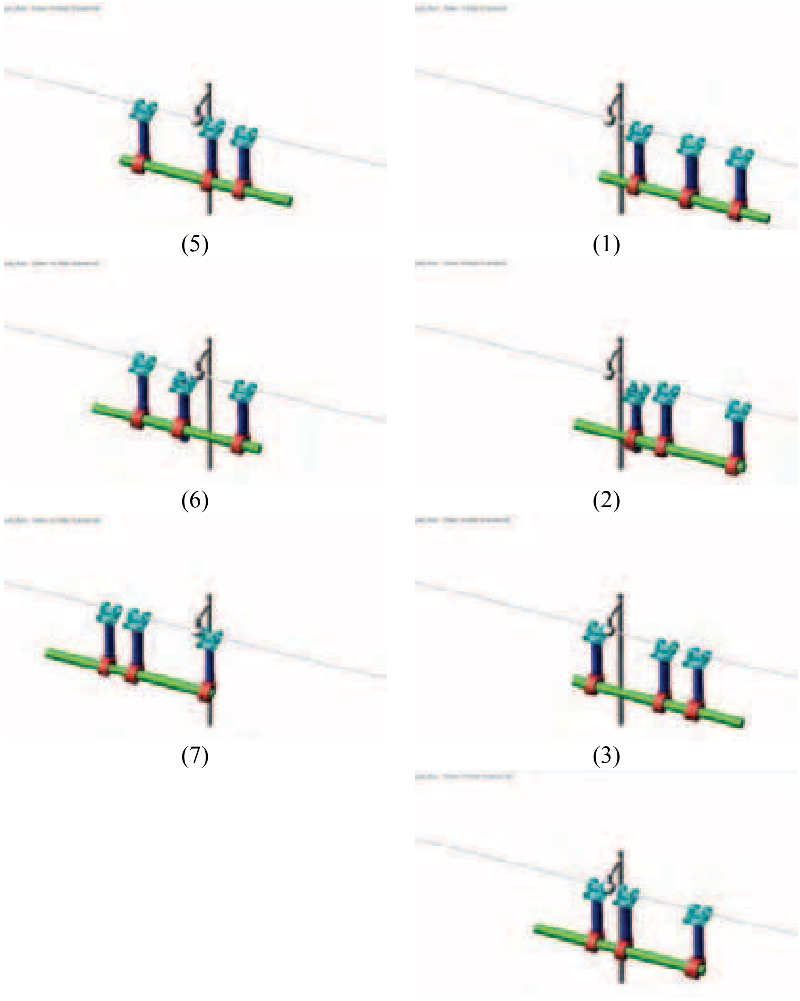


Fig. 15. Proposed mechanism by Nayyerloo et al., 1) the gripping mechanism, 2) the driving system, 3) one of the three arm mechanisms, and 4) the arm driving mechanism (Nayyerloo et al., 2007)

When the robot detects an obstruction, the gripper of the closest arm to the obstacle opens, and the arm goes down to avoid contact. The next step is translating the arms forward by fixing the middle arm to the line and driving the robot's main screw to pass the front arm to the other side of the obstacle. When the front arm passes the obstacle, it goes up and grips the line on the other side of the obstruction (1-3 in Figure 16). At this stage, the robot needs to make enough room on the other side of the obstacle to transfer the middle arm. This will be done by fixing the front and rear arms' grippers to the line and driving the main screw to move the middle arm as close as possible to the obstacle, and then fixing the middle arm to the line and moving the front and rear arms forward (4 and 5 in Figure 16). To transfer the middle arm to the other side of the obstacle the front and rear arms' grippers grasp the line, the middle gripper is detached from the line, the middle arm goes down, and the main screw is driven to move the middle arm under the obstruction. The middle arm grasps the line on the other side of the obstacle and makes the robot stable to pass the rear arm (6 and 7 in Fig 16). Following the same concept, the rear arm passes the obstacle, and the robot returns to its original configuration.



(5) (1)

(6) (2)

(7) (3)

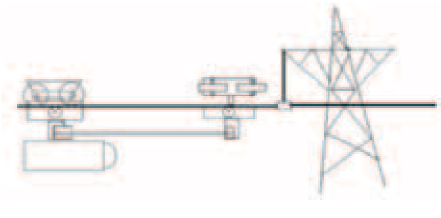
(4)

Fig. 16. Obstacle traversing mechanism proposed in (Wolff et al., 2001) and (Nayyerloo et al., 2007)

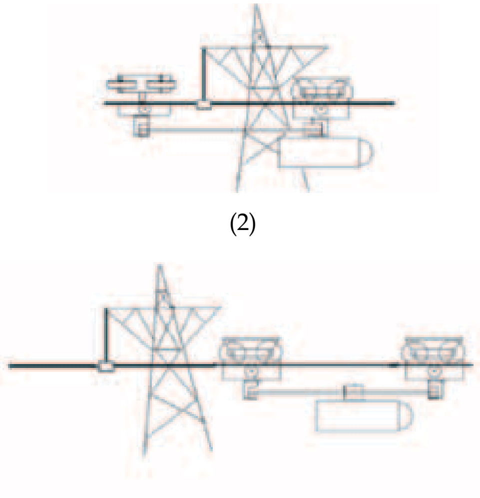
The proposed mechanism is simple to control, fast, and stable in overcoming obstacles. Even in windy climates, the three flexible arms can lift the robot body and make it as close as possible to the line to avoid swinging with large amplitudes. Another interesting feature of the proposed mechanism is its capability to navigate on paths with different shapes i.e. the robot's path could be even non-parabolic. The lengths of the robot arms can be adjusted according to the slope of the navigating path to keep the robot horizontal in all situations during the movement. The robot also has three hinged joints at the end of each arm that allow the grippers to be adjusted according to the slope of the line i.e. only grippers are sloped and the arms remain vertical in all situations. Besides the advantages of the proposed mechanism, it still needs to be modified to be able to pass tension towers with angled lines.

Another interesting obstacle traversing mechanism for power lines inspection robots proposed by (de Souza et al., 2004). The obstacle overcoming procedure is shown in Figure 17. The configuration in this figure has two sets of three wheels to move the robot along the line. When the robot detects an obstacle following obstacle avoidance procedure is followed: the box in middle of the robot, which contains all the required inspection tools, moves back along the track, the front set of wheels releases the line and rotates, the rear set of wheels is moved to surpass the obstacle (1 in Figure 17), and the front set of wheels grips the cable on the other side of the obstacle. Next, the box is moved forward to the other end of the track, the rear set of wheels releases the line and rotates then the robot moves until the rear set of wheels surpasses the obstacle (2 in Figure 17). The rear wheel set grasps the line again, and the robot goes back to its original configuration (3 in Figure 17). The same concept in obstacle overcoming mechanism, as shown in Figure 18, was also used by Sun et al. (Sun et al., 2006), but without centroid adjustment. In this work, the authors tried to optimize the mechanism design through using some simulation and analysis softwares such as Pro/E and ANSYS. Thus, both designs are simple, stable, and fast in obstacle avoidance, but they apparently cannot pass the tension towers and transfer to angled lines. Moreover, such mechanisms should be modified to be able to overcome the obstructions such as warning spheres, which have more protrusion from the line than the clamps.

Another interesting cable-climbing mechanism, which is similar to the works in (de Souza et al., 2004) and (Sun et al., 2006) with a modification in arms movement, was presented by Fu et al. in 2006. Their inspection robot, shown in Figure 19, has two arms with driving wheels mounted on top of each arm. The arms can go up and down, and the driving wheels, which are combined with a gripper mechanism to grasp the line when it is required, can move the robot along the line. When the robot encounters an obstacle ahead, the main body is moved forward to balance the robot's weight according to the front arm position. Next, the rear arm raises its driving-gripping set from the line, passes the obstacle, and lowers down to grasp the line on the other side of the obstacle. To pass the front arm to the other side of the obstacle, the robot needs to balance its weight according to the rear arm position. Next, the front arm releases the line, goes up, and passes the obstacle. In this procedure, the rear arm becomes the front arm and vice versa. When the both arms pass the obstacle, the robot should go back to its original configuration again (Fu et al., 2006).



(1)



(2)

(3)

Fig. 17. Obstacle traversing mechanism proposed in (de Souza et al., 2004)

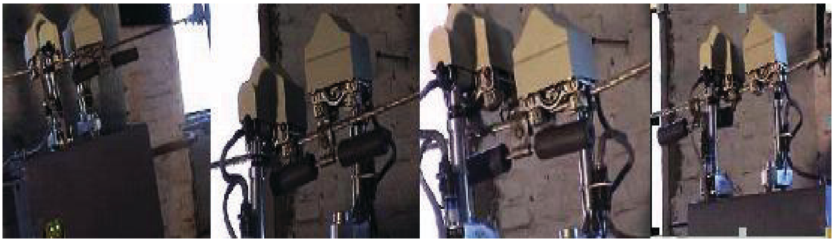


Fig. 18. From left to right, obstacle overcoming process in (Sun et al., 2006)

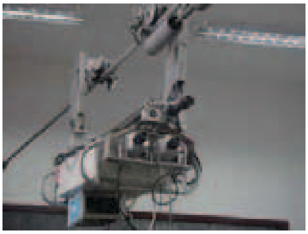
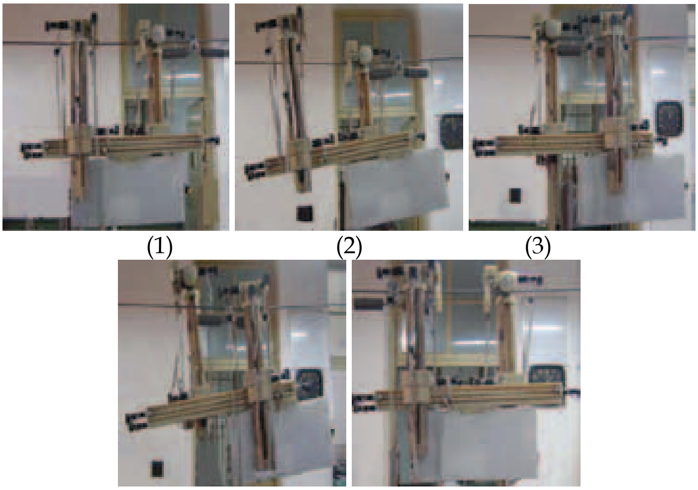


Fig. 19. The cable-climbing robot presented in (Fu et al., 2006)

Similar work to the project accomplished by Fu et al. has been recently carried out by Ren and Ruan. As shown in Figure 20, similar method has been used for navigation and obstacle traversing in (Ren & Ruan, 2008). These two mechanisms can only pass obstructions with small protrusion from the line such as different kinds of clamps and dampers, and more importantly, these two mechanisms cannot transfer to the angled lines.

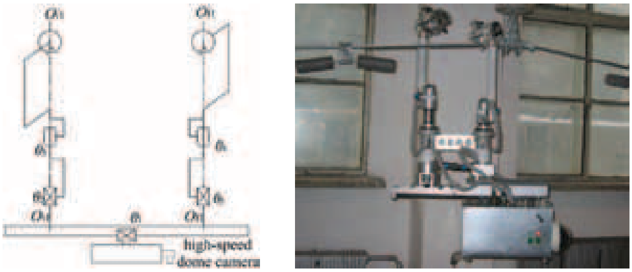


(1) (2) (3)

(4) (5)

Fig. 20. Obstacle traversing mechanism proposed in (Ren & Ruan, 2008).

One of the most simple and efficient mechanisms, which resolves some of the issues in (Fu et al., 2006) and (Ren & Ruan, 2008), proposed by Zhu et al. in 2006. The robot configuration, as shown in Figure 21 (a) and (b), has two arms equipped with a special gripper combined with a driving wheel. This special running-gripping mechanism has been shown in Figure 22. When the robot detects an obstacle on its way, it stops, grasps the conductor with the front gripper and moves its main body under the front arm in order to minimize the required torque needed for crossing the obstacle (Figure 23 (a)). Next, the rear arm lifts the rear running wheel up, and the front arm rotates the whole robot around its own axis. Finally, the rear arm lowers its wheel set on the conductor (Figure 23 (b)), and then the same process is repeated with the arms' roles changed. Such an obstacle traversing strategy makes the robot's arms simple with only two degrees of freedom. Also the required torques in the joints and on the line will be small enough, thus there is no need for the heavy and powerful motors.



(a) (b)

Fig. 21. Robotic mechanism configuration proposed by Zhu et al.: (a) sketch of the robot's configuration, and (b) the robot prototype (Zhu et al., 2006)

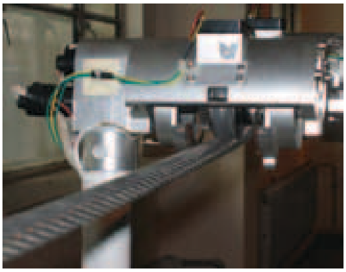


Fig. 22. Special running-gripping mechanism proposed in (Zhu et al., 2006)

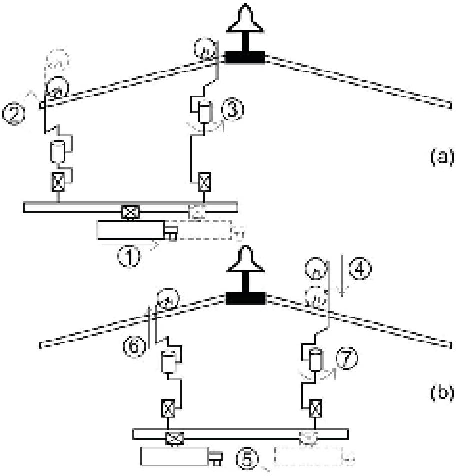


Fig. 23. Obstacle avoidance procedure proposed by Zhu et al. (Katrasnik et al., 2008)

The proposed mechanism is simple, stable and efficient. Moreover, with some minor modifications in the gripper design to increase the contact area between the gripper and the line, the robot will be even more stable in windy climates. Another interesting feature that the proposed mechanism can provide with minor changes in the existing gripper design is the ability to transfer to angled lines. The robot rotation angle about the arms' axes in the obstacle avoidance procedure can be adjusted to the angle of the line ahead, thus the robot can easily transfer to an angled line, but as in this situation, the grippers are not parallel to each other, they should be able to rotate about the arms' axes to be able to adjust themselves to the line angle.

The mechanism has a minor disadvantage that should be taken into account when dealing with acquired inspection or navigation data. When the robot passes an obstacle, it has to rotate 360° around the arms' axes. Hence, the installed inspection or navigation sensors on the robot body, such as image system, will rotate 360° under the obstacle to pass it. This rotation in the robot main body has been missed out in both the original work and (Katrasnik et al., 2008). It therefore has not been shown in Figure 23, which has been taken from the latter work. This rotation may cause some undesirable inspection or navigation data.

One of the most important efforts to develop an operational cable-climbing mechanism has been made by Montambault and Pouliot over the past five years. Their teleoperated robot, LineScout, shown in Figure 24, is the third generation of its previous prototypes designed by this team. LineScout uses driving wheels for locomotion. These wheels allow the robot to not only move quickly along the power line, but also to roll over some obstacles e.g. compression splices and vibration dampers. To clear other types of obstacles, the robot follows the approach schematized in Figure 25 (a). As shown in this figure, LineScout has three independent frames: the wheel frame (dark frame), which includes two motorized wheels called "traction wheels", the arm frame (light frame), with two arms and two grippers, and the center frame (white circle), which is called "extremity frame". This frame links the first two frames together and allows them to slide and pivot (Montambault & Pouliot, 2007). As an obstacle is detected, the arm frame is opened, and its two arms and grippers temporarily support the robot while the wheel frame is being transferred to the other side of the obstacle with the wheels flipped down under the obstacle. The wheel frame also includes a pair of safety rollers (small rectangles beside the driving wheels) for platform stability when crossing obstacles. The center frame supports the electronics cabinet and battery pack. The role of the center frame is generating the movements of the two other frames by sliding them in opposite directions and also supporting about 40% of the platform's weight to minimize the cantilevered load applied when the two other frames are in total extension during the obstacle clearance sequence as shown in top picture in Figure 25 (b).

Although the appropriateness of the proposed line inspection robot has been shown through several lab and field tests for straight lines between suspension towers, the mechanism still needs to be modified to be able to pass the tension towers with angled lines. However, it surpasses all its previous designs in terms of considering different real field requirements such as resistance to intensive electro-magnetic field and durability of the inspection task that are vital toward having an operational inspection robot.

In order to decrease the above mentioned complexities in designing a versatile cable-climbing mechanism capable of clearing all types of the obstructions and able to transfer to the angled lines on various power transmission lines, a new type of robot proposed by Katrasnik et al. in 2008 (Katrasnik et al., 2008). The idea is based on the combination of a flying robot such as (Williams, 2000) or (Golightly & Jones, 2005) with a cable-climbing robot to navigate on the power lines. The proposed flying-climbing robot, schematized in Figure 26, removes all the complexities in the mechanical mechanism design arising from the obstacle avoidance system by flying over the obstacles or flying from one span to another span to pass the towers. The implemented cable-climbing mechanism, which is the default navigation system of the robot on the line between the obstacles, ensures stability in navigation and provides performing the inspection from close distances to the line that is necessary for various line inspection sensors such as corrosion detectors. Using the climbing mechanism as the default navigation system also removes the flight control complexities in existing flying inspection robots when the robot navigating between the obstacles.

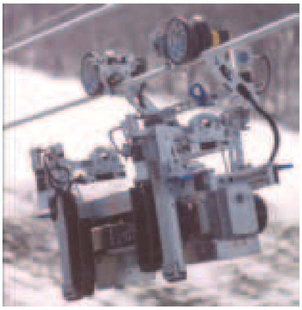
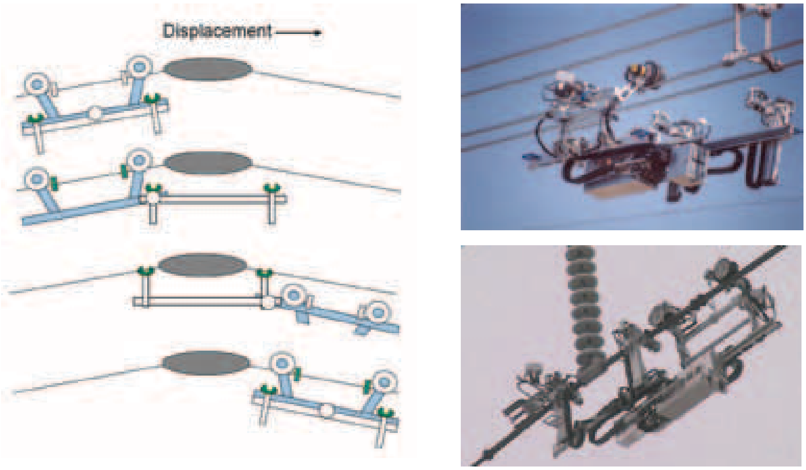


Fig. 24. LineScout mobile platform (Montambault & Pouliot, 2007).



(a) (b)

Fig. 25. LineScout obstacle-clearing sequence: (a) schematic of the obstacle-clearing procedure (Pouliot & Montambault, 2008) and (b) LineScout clearing obstacles in real working conditions (Montambault & Pouliot, 2007)

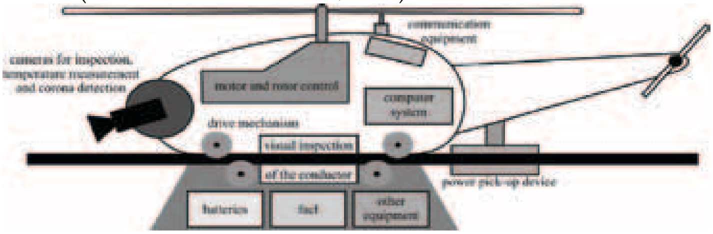


Fig. 26. Flying-Climbing robot (Katrasnik et al., 2008)

Katrasnik et al. have compared the two possibilities in the power lines inspection robot design, flying and climbing, with their novel mechanism proposed in (Katrasnik et al., 2008). The results are shown in Table 1. As the table shows, four major criteria have been chosen for this comparison: Availability and simplicity of the robot's design and construction, quality of the acquired inspection data, fully autonomous inspection, and adaptability to different situations on the power lines or universality. The comparison criteria have been sorted in order of importance and appropriate weight, as shown in Table 1, has been given to each criterion.

	w	Climbing	Climbing-Flying	Flying
Design and Construction	4	1|4	2|8	3|12
Inspection quality	3	2|6	3|9	1|3
Autonomy	2	3|6	2|4	1|2
Universality	1	1|1	2|2	3|3
Total score		17	23	20

w=weight, rank | weighted score

Table 1. Robot type comparison table (Katrasnik et al., 2008)

Various types of unmanned aerial vehicles (UAVs) are commercially available, and there is no need to start from scratch and build a new flying platform for inspection of the power lines. Hence, the highest point in the first criterion has been given to the flying robot. Also with some modifications on available UAVs in the market, the climbing-flying robot is achievable, thus the second highest scored design is the climbing-flying robot.

To compare the inspection data quality, the most problematic case is the flying robot (Katrasnik et al., 2008). Vibrations of the flying platform and its distance to the power lines during the inspection affect quality and resolution of the captured images, which are the main inspection data. The climbing mechanism has less vibration than the flying robot due to the line support and has been ranked higher than the flying robot. The climbing-flying robot can inspect the line equipment (obstacles) from additional angles when it flies over them. In that, the highest grade has been given to the climbing-flying robot.

In terms of autonomy, due to complexity of the flight control, making a fully autonomous flying robot is certainly more difficult than developing an autonomous climbing mechanism. Moreover, when the robot is attached to the power line, the required power can be supplied through the live-line that makes the robot more independent and autonomous.

The last evaluation item in Table 1 is the universality of these three mechanisms. The flying robot is completely unattached to the power lines, and thus has more maneuverability over different power lines. The climbing-flying robot needs some modifications in the climbing side to be adapted to different conductor sizes, but the climbing robot needs major modifications especially to be able to pass different obstacles. In that, the highest score has been given to the flying robot, followed by the flying-climbing mechanism, and the lowest scored design in terms of universality is the climbing robot.

4. Conclusions

Uninterruptable electricity supply to a vast number of customers has utmost importance for power companies. Therefore, regular live line inspection is a vital task for the power companies to find damage to the line to prevent likely blackouts. The most desirable inspection method in dangerous live-line environment is certainly a fully autonomous method without human operator intervention.

Traditional patrol inspection using helicopters is costly, do not provide a platform for precise inspection of the line from close distances, and due to the risk of contact with the live line in windy climates still is not sufficiently safe for the operators. In that, researchers have endeavored to build robots capable of performing the live line inspection autonomously.

Unmanned aerial vehicles and cable climbing robots are the two main categories of the power line inspection robots. UAVs are complex in control and do not provide an appropriate platform for internal inspection of the conductors. For instance, corrosion detector sensors, which examine the line from a close distance, cannot be used on such platforms. However, as UAVs fly over the power lines, their design is not directly dependent on geometrical characteristics of the lines. Moreover, these flying robots have been already commercialized and can be modified for live line applications. The second main category, the climbing robots, are much more dependent on the line equipment than the flying robots in terms of size and shape of the obstacles on the lines, surrounding electromagnetic field, voltage level of the line, etc.

Climbing robots should be specifically designed for the power lines from scratch. They are not currently available on the market, but they provide more autonomy and inspection data quality. The climbing platforms also allow more accessibility to variety of inspection sensors than the flying robots. This unique feature has been made research in the cable-climbing mechanism design popular.

This chapter reviewed some of the main efforts made over the past 20 years in the field of cable-climbing mechanism design to provide a basis for future developments in this field. History of the research in this field shows that due to the huge benefit of early detection of likely damage to the line, even the cable-climbing robots capable of only climbing on part of the line between two obstacles are in use, and further researches in this field will definitely benefit the power companies to efficiently manage their assets. In addition, based on the reviewed works, a flying-climbing platform which is a commercially available UAV modified with a cable-climbing mechanism would enormously benefit the line inspection quality and the design universality.

5. References

Aggarwal, R. K.; Johns, A. T.; Jayasinghe, J.A.S.B. & Su, W. (2000). An overview of the condition monitoring of overhead lines, *Electric Power Systems Research: An International Journal,* No. 53, 2000, pp. 15-22, Elsevier Science S.A., PII: S0378-7796(99)00037-1

Aoshima, S.; Tsujimura, T. & Yabuta, T. (1989). A wire mobile robot with multi-unit structure. *Proceedings of the IEEE/RSJ International Workshop on Intelligent Robots and Systems*, pp. 414-421, Tsukuba, Japan, September 4-6, 1989.

Campos, M. F. M.; Bracarense, A. Q.; Pereira, G. A. S.; Pinheiro, G. A.; Vale, S. R. C. & Oliveira, M. P. (2002). A mobile manipulator for installation and removal of aircraft warning spheres on aerial power transmission lines. *Proceedings of the IEEE International conference on Robotics and Automation*, pp. 3559-3564, Washington DC, USA, May 2002.

Cormon Ltd Corrosion Monitoring Systems (1998). Overhead line corrosion detector. Data Sheet No. PTP 002, Rev. 04/98, available at: http://www.cormon.com

de Souza, A.; Moscato, L. A.; dos Santos, M. F.; de Britto Vidal Filho, W.; Ferreira, G. A. N. & Ventrella A. G. (2004). Inspection robot for high-voltage transmission lines. *ABCM Symposium Series in Mechatronics,* Vol. 1, pp. 1-7, 2004, Available from: www.abcm.org.br/symposiumSeries/SSM_Vol1/Section_I_Robotics/SSM_I_01.pdf , Accessed: 27-Sep-2008.

Fu, S.; Li, W.; Zhang, Y.; Liang, Z.; Hou, Z.; Tan, M.; Ye, W.; Lian, B. & Zuo, Q. (2006). Structure-constrained obstacle recognition for power transmission line inspection robot. *Proceedings of The IEEE/RSJ International Conference on Intelligent Robots and Systems,* pp. 3363-3368, Beijing, China, October 9-15, 2006, Available from: http://ieeexplore.ieee.org/

Golightly, I. & Jones, D. (2005). Visual control of an unmanned aerial vehicle for power line inspection, *Proceedings of The 12th International Conference on Advanced Robotics (ICAR '05),* pp. 288-295, Seattle, WA, USA, July 18-20, 2005, Available from: http://ieeexplore.ieee.org/

Higuchi, M.; Maeda, Y.; Tsutani, S. & Hagihara, S. (1991). Development of a mobile inspection robot for power transmission lines. *The Journal of Robotic Society of Japan,* Vol. 9, No. 4, pp. 57-63 (in Japanese)

Katrasnik, J.; Pernus, F. & Liker, B. (2008). New robot for power line inspection, *Proceedings of the IEEE International Conference on Robotics, Automation and Mechatronics (RAM),* pp. …-…, Chengdu, China, September 21-24, 2008.

Montambault, S. & Pouliot, N. (2007). Design and validation of a mobile robot for power line inspection and maintenance. *Proceedings of the 6th International Conference on Field and Service Robotics (FSR),* pp. 1-10, Chamonix, France, July 9-12, 2007, Available from: http://hal.inria.fr/inria-00194717/fr , Accessed: 13-Oct-2008.

Nayyerloo, M.; Yeganeh-parast, S. M. M.; Barati, A. & Saadat Foumani M. (2007). Mechanical implementation and simulation of MoboLab, a mobile robot for inspection of power transmission lines. *International Journal of Advanced Robotics Systems,* Vol. 4, No. 3, 2007, pp. 381-386, ISSN 1729-8806

Pouliot, N. & Montambault, S. (2008). Geometric design of the LineScout, a teleoperated robot for power line inspection and maintenance. *Proceedings of The IEEE International Conference on Robotics and Automation,* pp. 3970-3977, Pasadena, CA, USA, May 19-23, 2008, Available from: http://ieeexplore.ieee.org/

Ren, Z. & Ruan, Y. (2008). Planning and control in inspection robot for power transmission lines. *Proceedings of The IEEE International Conference on Industrial Technology (ICIT),* pp. 1-5, Chengdu, China, April 2008, Available from: http://ieeexplore.ieee.org/

Sato Kensetsu Kogyu Co., Ltd. (1993). Automatic overhead power transmission line damage detector. available at: http://www.sato-k.co.jp/technology/sonshou-e.html accessed: 6-Oct-2008.

Sawada, J.; Kusumoto, K.; Munakata, T.; Maikawa, Y. & Ishikawa Y. (1991). A mobile robot for inspection of power transmission lines. *IEEE Transactions on Power Delivery,* Vol. 6, No. 1, pp. 309-315

Sun, C.; Wang, H.; Zhao, M. & Liu, H. (2006). 3D simulation and optimization design of a mobile inspection robot for power transmission lines. *Proceedings of The 6th World Congress on Intelligent Control and Automation,* pp. 8986-8991, Dalian, China, June 21-23, 2006, Available from: http://ieeexplore.ieee.org/

Tang, L.; Fang, L. & Wang, H. (2004). Development of an inspection robot control system for 500kV extra-high voltage power transmission lines, *Proceedings of The SICE Annual Conference,* pp. 1819-1824, Sapporo, Japan, August 2004, Available from: http://ieeexplore.ieee.org/

Tsujimura, T. & Morimitsu, T. (1997). Dynamics of mobile legs suspended from wire. *Robotics and Automation Systems: An International Journal,* No. 20, 1997, pp. 85-98, Elsevier Science S.A., PII S0921-8890(97)00019-5

Williams, M. (2000). Investigation on machine vision and path planning methods for use in an autonomous unmanned air vehicle, Ph.D. Thesis, School of Informatics, University of Wales, Bangor, England, December 2000.

Wolff, A. and Khajepour A. (2001). A crawling robot for high voltage power lines inspection, Senior Design Project, University of Waterloo, Department of Mechanical Engineering, Waterloo, Ontario N2L 3G1, Canada, 2001.

Zhu, X.; Wang, H.; Fang, L.; Zhao, M. & Zhou, J. (2006). A novel running and gripping mechanism design based on centroid adjustment, *Proceedings of The IEEE International Conference on Mechatronics and Automation,* pp. 1471-1476, Luoyang, China, June 2006, Available from: http://ieeexplore.ieee.org/