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A Roadmap for Automated Power Line Inspection, Maintenance and Repair.

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Abstract

Today, power line operators perform visual inspection to check the status of their transmission lines mainly by using helicopters equipped with external gimbals housing infrared and ultraviolet cameras to detect hot spots and corona discharges. This solution is quite expensive, dangerous for the crew and not very reliable. Future power grids integrating remote eco-power like wind and sun will require a much intensive supervision due to the high load and the rising vulnerability of the network. A project was initiated at Fraunhofer IPA to explore the feasibility of a totally automated system capable of a rigorous live line inspection strategy based on a completely autonomous mobile platform. Focus of this paper is, presenting the state of the art of the most important current projects concerning the two main categories of robots offering a solution of automation, vertical take-off and landing (VTOL) unmanned aerial vehicles (UAVs) and rolling on wires robots (RWR), to create a roadmap for researchers and industries to implement a *"FULLY AUTOMATED LIVE LINE POWER LINE INSPECTION CONCEPT"*: including a power line data management system with specific tool for image and signal data processing to automatically detect defects or abnormal conditions.

Keywords: Fully Automated Power Line Inspection Concept; RWR; VTOL UAVs; Power Line Data Management System

1. Introduction

Considering the progressive development of new green power generation plants, the need for a higher and more reliable electrical transport capacity is growing up in Europe (Fig. 1). Since new electric power transmission line installations are difficult to be accepted by the public, the existing systems have to be upgraded. The consequence is that the lines are always operated at the maximum load and there are no redundancies or reserves to compensate breakdowns. Preventive maintenance is therefore of extreme importance.

In particular the high-voltage lines, usually, crossing thousands of kilometers in suburban environments, mountains and forests, are often exposed for long period to hard environment conditions such as thermal excursions, rain, ice, wind, induced vibration, heavy temperatures, and aggressive agents (sour rains). These causes, together to the corrosion, more remarkable in areas affected by high pollution and sudden changing in temperature and humidity [2], induce fatigue ruptures that reduce the life time of the lines and high losses. In addition lightning bolts can also cause severe damaging as ruptures in strands and partial melting of wires.

Electrical power companies perform regular visual inspection mainly by using helicopters equipped with external gimbals housing daylight camera, infrared camera to detect hot spots (damages on the cables and insulators have usually a direct consequence on their electrical resistance and therefore cause a local increasing in temperature) and ultraviolet camera to detect corona discharge (defective components cause a local electrical field increment and when it exceeds a critical value the air is ionized leading to emission of UV radiation) [3]. However this solution is quite expensive (≈1000 €/h), dangerous for the crew (the flight regime is low, slow and near the live line) and not very reliable. It can, in fact, provide images of only the upper part of the cables, and critical failures such as internal corrosion of the steel reinforced aluminum conductors (ACSR) cannot be detected. Also manual visual inspection is widely applied.

Considering this background, focus of this project is to create a roadmap that can guide researchers and industries in the implementation of a "*FULLY AUTOMATED LIVE LINE POWER LINE INSPECTION CONCEPT*": a rigorous live-line inspection strategy based on a completely autonomous mobile platform providing a sufficient payload and a power line data management system including specific tool for image and signal data processing to automatically detect defects or abnormal conditions. In this way the reliability of the electric power supply will be increased and in the same time the costs reduced.

Fig. 1. 110 kV overhead lines [1]

In [4] and [5], power line robots are considered as "high-value applications" and key components in the developing a "smart transmission grid". In addition it is also examined that the main economical benefits of this new technology will be received not in the replacing linemen but in extending the linemen´s own capabilities to make optimal maintenance and repair decisions.

2. Power line inspection robots

In the current state-of-the-art there are two main categories of power line inspection robots: vertical take-off and landing (VTOL) unmanned aerial vehicles (UAVs) and rolling on wires robots (RWR).

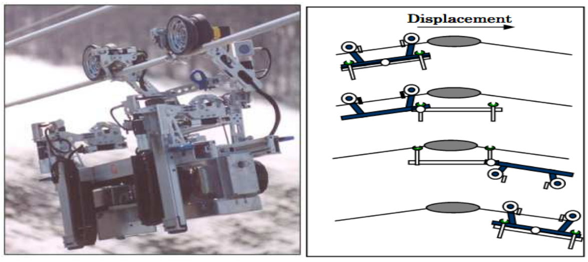
2.1. Rolling on wires robots - research projects -

In North America, at Hydro-Québec´s research institute (IREQ), a division of Hydro-Québec TransÉnergie that generates, transmits and distributes electricity, three different robotic technologies on complete systems have been developed since 1998 [6].

The first, LineROVer Technology, a remotely operated trolley, operative in 2000, is described in [7] [8]. Although, initially developed for de-icing is also used on live 315-kV for visual and infrared inspections, measuring compression, splice, electrical resistance and replacing old conductors and overhead ground wires using the cradle-block stringing method.

The second technology, developed in 2003, was designed to operate on two-, four-, and six- conductor bundles. It can cross obstacles found on the wires, including space-dampers and suspension clamps, in about 1 s [9].

The third, LineScout Technology, (Fig. 2, a) presented in [11], [12], [13] was first used on the Hydro-Québec transmission network in 2006 in teleoperated control. It is designed to travel along single energized conductors, including one of the conductors of a conductor bundle, and is immunized to electromagnetic and radio-frequency interferences (EMI/RFI) from lines of up to 735 kV [6].



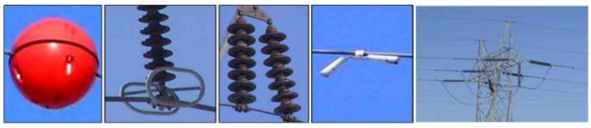
(a) (b)

Fig. 2. (a) LineScout Technology; (b) obstacle-clearing sequence [10]

Its mechanical structure, capable to cross warning spheres (0,76m diameter), corona rings, double insulator strings and vibration dampers (Fig. 3), is based on two extremity frames and a centre frame (Fig. 2, b). All are independent from each other. The extremity frames are composed by a wheel frame (dark frame) and an arm frame (light frame). The wheel frame includes two rubber traction wheels and a camera mounted on a pan-and-tilt unit. The arm frame, consists of two arms and two grippers including two cameras on a pan-tilt unit and most of other optionale application modules. The centre frame (white circle) hosts the electronics on board and the battery pack. In addition it links the extremity frames and allow them to slid and rotate. In proximity of an obstacle in fact, the arm frame slides in a way that the two arms and grippers can temporarily support the robot while the wheel frame, rotated under the obstacle slides until it reaches the other side of the obstacle [10]. The obstacle-crossing sequence takes less than 2 min. The mechanical system is capable to overcome obstacles up to 0,76 m in diameter (warning spheres) and it is not limited to a specific distance between adjacent obstacles. This makes the system very versatile, but however crossing dead end structures and jumper cables (Fig. 3, e) were not included in the design specifications [6]. More detail about the geometrical analysis focalized on the optimization of the platform's structure can be found in [14].

LineScout has a top linear speed of 1 m/s, weights 98 kg and provides autonomy for 5 hours operation.

In Fig. 4 [6], three installation methods are shown developed and validated by line maintenance personnel, using an insulated boom truck on a 69-kV circuit (Fig. 4, a), an insulated rope on a 735-kV (fig. 4, b), and an installation on the overhead ground wire (OGW) above double 315-kV circuits (Fig. 4, c).



(a) (b) (c) (d) (e)

Fig. 3. (a) warning spheres, (b) corona rings, (c) double insulator strings, (d) vibration dampers [10], (e) jumper cable located at an angle tower [6]

(a) (b) (c)

Fig. 4. installation methods: (a) on a 69-kV circuit, (b) on a 735-kV, (c) on OGW above double 315-kV circuits [6].

A collaboration between IREQ and the Research and Development Department of the British Columbia Transmission Corporation (BCTC) started in 2006.

BCTC that plan, build, operate and maintain British Columbia's electricity transmission system with over 18,000 km of power transmission lines established a Technology Roadmap concerning four broad categories: *Energy Security; Conservation, Efficiency and Environmental Leadership; Smart Grid; Future Grid*. In particular, in the latter, is outlined the implementation of automated inspection applications utilizing advanced technologies: line robots, UAVs, tele-operated arms, utilizing inspection devices such as high resolution visual, infrared and hyper-spectral cameras, corona probes, resistance measurements and other non-destructive test (NDT) methods, are considered as an important opportunity to improve in the field working methods productivity and worker safety [15].

The cooperative work between BCTC R&D and IREQ resulted in highly valuable data for BCTC and in improvement of the LineScout Technology being tested in different geographical, meteorological and operational environments [16]. Splash resistance became necessary: Hydro-Québec operates in fact in a cold, dry environment while in British Columbia sudden rain showers are common even in seasons considered dry. In addition new installation and removal methods were developed and new sensors were utilized [16].

In June 2010 this collaboration earned the highest electrical utility award from the Edison Electrical Institute, the Edison Award in the International Affiliate category [16].

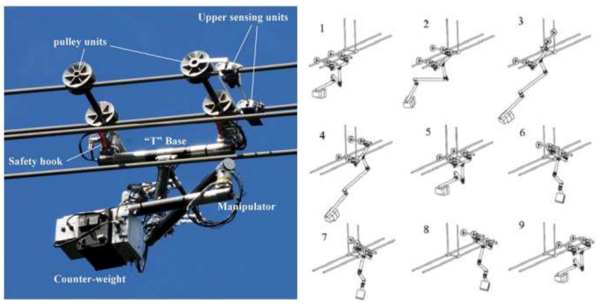
In Japan, HiBot Corp., in a joint project with Kansai Electric Power Corporation (KEPCO) and Tokyo Institute of Technology, has developed in 2008 Expliner [17].

This robot is designed for inspection up to 4 cables grouped in a bundle, and has been extensively tested in live lines up to 500kV. Its mechanical carbon fiber structure (fig. 5, a) is composed of two pulley units, a T-shaped base, a counter-weight and a manipulator with 2 degrees of freedom.

Expliner carries four sensing units to inspect up to 4 cables simultaneously. The sensing units incorporates visual camera able to get images of the entire surface of the cables and laser sensors capable to identify changes in the diameter in the order of 0.5mm to detect internal corrosion along the line.

In fig. 5, b is showed the obstacle-overcoming sequence. In proximity of a suspender clamp, the front pulleys are lifted up by moving its counter-weight to the rear side, and then rotates outside so that Expliner can move forward until the front pulleys have crossed the obstacles. The front pulleys are then rotated back inside, the manipulator moves the counter-weight until the center of mass is back to the center and the front pulleys are back on the transmission lines but behind the obstacle. The same procedure is repeated with the rear pulleys by moving the counter weight forward.

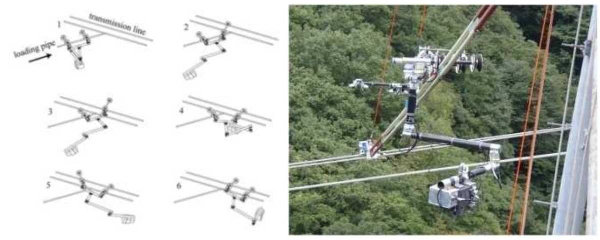
Expliner weights 80 kg and provides autonomy for 6 hours operation.



(a) (b)

Fig. 5. (a) Expliner and its main components [17]; (b) obstacle-overcoming sequence [17].

The operational procedure to position Expliner on transmission lines is an outstanding feature of the system. Instead of lifting the robot and using very long insulated rods to adjust his relative position on the live-line, a tower is connected to the line with a pipe called "loading pipe". Expliner, assembled on the ground and placed on the tower, rolls on the loading pipe until it reaches the final extremity. At this point, since the loading pipe and the line are not aligned, Expliner performs a complex obstacle-crossing motion called "Acrobatic Mode" (Fig. 6). It is always based on the changing the position of the counter-weight backward/forward and lifting and rotating (this time the rotational angle depends on the angle formed between the loading pipe and the transmission line) respectively the front/ the rear pulleys.



(a) (b)

Fig. 6. (a) Expliner´s Acrobatic Mode; (b) Expliner moving on the loading pipe

In total 2h35min are required to set the loading pipe and all necessary infrastructure, and 45 minutes are necessary for Expliner to move along the loading pipe and to enter in the transmission line. However pre-equipping the line the overall time could be strongly decreased.

Expliner is the winner of the 4th Robot Award (Japan Ministry of Economy, Trade and Industry).

2.2. Vertical take-off and landing unmanned aerial vehicles for power line inspection - research projects -

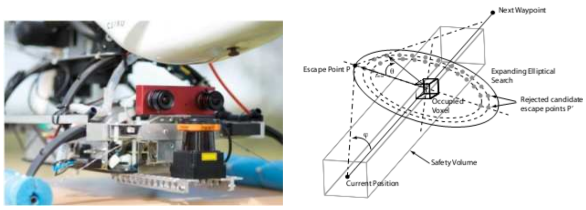
In Australia, researchers at Australian Research Centre for Aerospace Automation (ARCAA), a joint venture between the Commonwealth Scientific and Industrial Research Organization (CSIRO) Information & Communication Technologies (ICT) and the Queensland University of Technology (QUT), have been working on automated sensing, control and navigations systems in order to develop an autonomous helicopter for power line inspection which requires minimal operator involvement [18] [19]. The helicopters used as platform (fig. 7, a), are first commercial radio controlled helicopters, powered by a 23cc two-stroke gas engine, 1.8 m rotor diameter, 55 min. endurance with 1,2 l fuel, maximum takeoff weight of 12,3 kg (base platform 7,7 kg, 4,6 kg for fuel, sensors and flight computers) [20], and also an autonomous helicopter (T21) (Fig. 7, b) [21] [22], powered by micro-turbine, 2,2 m rotor diameter, 1 – 1,5 hrs endurance, maximum take off 30 kg (empty weight 15 kg).

Their activity in particular has concentrated to develop obstacle detection and path planning for avoidance using stereo vision and laser scanning (Fig. 8, a) to generate a 3D Occupancy Map of the environment [20].

(a) (b)

Fig. 7. (a) commercial radio controlled helicopter [20]; (b) T21 [21]

The stereo camera (8mm lens, field of view 27°×20°) can detect obstacles such as trees and steel towers at 30m with an error of approx 2m. The laser scanning (270° field of view, maximum range of 30m, 40 Hz update rate) can detect steel structures at 30 m but trees and bushes at only approximately 20 m depending on the reflexive properties of the feature being sensed. The concept of the obstacle detection and avoidance is illustrated in Fig. 8, b. From the UAV´s current position, a "*safety volume*" is projected forwards along the current flight path until the next waypoint is reached. If an obstacles O is detected within the Safety Volume, an "*Escape Point*" P is searched in free space expanding ellipses having a radius at least a minimum distance from the detected obstacles, centered in O, and perpendicular to the vector joining the current UAV position to the goal waypoint. Once the Escape Point is reached the original goal waypoint is reconsidered.



(a) (b)

Fig. 8. (a) stereo camera and laser scanner [20]; (b) safety volume, escape point P, expanding elliptical search [20]

In Spain, at Polytechnic University of Madrid research activities are focused on development of techniques that use visual information as main input for autonomous navigations of UAVs towards features of interest when GPS signals are not reliable or sufficient. [23]. The platforms used are a gas powered Industrial Twim 52 c.c helicopters and a Rotomotion SR20 UAV with an electric motor of 1,300 W, 8A. More precisely by GPS signals the UAV is directed and aligned in proximity of the structure of interest and from there visual tracking is used to determine position or velocity relative to the target. Image processing algorithms as Harris Corner detector, or SIFT (scale invariant feature transformation) detector are used to extract characteristics, called features, from the images that are then used as a reference for the visual flight control. Feature tracking algorithms, as Lukas-Kanade, are used to track features in consecutive images, giving the UAV the capability to follow objects. A visual stereo system is used on board the helicopter in a configuration looking down, perpendicular to the ground, and in another looking forward. The estimated distance, calculated matching features between left and right images and then using the disparity principle, corresponds thus in the first (looking down) configuration to the UAV altitude and in the second (looking forward) configuration to the distance between the UAV and an object. Image processing and feature tracking are fundamental aspects in the visual control loop. The flight control system is based on three control loops: the first governs the attitude of the helicopter interacting directly with the servomotors; the second, a velocity-based control, is responsible to generate the references for the attitude control; the third, a position based control, can be externally switched between the visual based controller and the GPS based position controller.

3. Conclusions

UAVs, especially for military operations, are a technology already worldwide implemented and several are their possible dimensions and characteristics (payload, endurance, ecc…). Several are also the available commercial VTOL UAVs and the academic research projects. Nevertheless UAVs customized to completely autonomous inspection of electrical power line, are still an emerging technology. Many concrete results are reached but however further improvements are still necessary. Further projects, considering in particular the specific constraints for a completely autonomous live line inspection can be in the following areas:

- Visual servoing for power line tracking (just a GPS system is not yet mature enough for an autonomous navigation capable to follow the lines and inspect the supports, but must be complemented with other systems)
- Obstacle detection and avoidance (considering the consequence of a crash in a live line) becomes an essential aspect for a reliable autonomous inspection system)
- Robust control algorithms for flight dynamics, ensuring a very high stability and positioning capability for close and precise inspections in particular in case of adverse weather conditions like strong lateral wind (in [24] BCTC identifies as requirement for a power line inspection UAV the capability to operate in 60 km/h wind)

Rolling on wires robots are more recent technologies but slowly are proving to be a very practical and valuable means to become part of the inspection standard working methods. The state-of-the-art in fact shows that many goal as, compact, reliable remotely operated locomotion system, obstacle crossing, significant payload, sufficient autonomy (about 18 km), and the capability to work without de-energizing high voltage lines (electromagnetic immunity) are reached. There are also other outstanding advantages and potentiality. Being, in fact, able to detect the status of the cable from close distances and allowing also contact measurements achieve a higher level of inspection data completeness. In addition they have the potential to increase the level of autonomy being powered directly from the live lines. However there are (also for the rolling on wires robots) some critical aspects that must be still developed to obtain a completely autonomous mobile inspection e.g. a platform that does not imply any human intervention. Future research projects therefore achieve:

- A completely autonomous navigation system capable to detect, identify and cross obstacles. Particular attention must be paid for broken strands. They, in fact, unlike the typical obstacles (warning spheres, dampers, insulators, ecc.) are present in unpredictable locations and do not have a well definite shape.
- A battery recharging system from the live line that can extend the autonomy up to several days combined with a more versatile mechanical concept capable to cross all types of obstacles (like jumper cable). With a traditional manned helicopter, usually 120 – 170 km of lines per day are inspected [27] and the cruising speed of a rolling on wires robots cannot be significantly incremented for safety reasons in case of broken strands. A good compromise to optimize the economic impact could be to extend properly the autonomy and to design an energy management system that during the dark hours can recharge the robots being so ready to work with the first lights of the day.
- A fast and automated installation method on the line. In [5] the authors consider that to maximize the benefits the installation on the live line should be within 30 minutes. For this point and for the inspection of other critical components of the line, like the insulators and the support structures, the VTOL UAVs, being able of quasi-static positioning could play a fundamental auxiliary role anchoring the rolling on wires robots on the lines contributing to make the entire process completely automated.

To complete the entire process, independent from the mobile platform utilized (VTOL UAVs and RWR), fundamental becomes also to develop a data management system including specific tool for image and signal data processing to automatically detect defects or abnormal conditions. In fact, huge quantity of data will be collected and it is also important to consider that the value of these mobile platforms lies properly in the payload namely in the completeness and accuracy of the data collected: visual, electrical, thermal, audible, ecc. Thus, an automated system capable to elaborate all the data stored and to plan for a maintenance management gives an essential additional value to optimize the benefits making a further difference with respect to the traditional inspection methods.

References

[1] www.eon-netz.com.

[2] Weischedel HR. The Magnetic Flux Leakage Inspection of Wire Ropes. NDT Technologies Inc; p.1– 19

[3] www.ofilsystems.com.

[4] Montambault S, Pouliot N. On the Economic and Strategic Impact of Robotics Applied to Transmission Line Maintenance. *7th International Conference on Live Maintenance (ICOLIM),* Romania: Bucharest; 2004.

[5] Montambault S, Pouliot N. About the Future of Power Line Robotics. *1st International Conference on Applied Robotics for the Power Industry,* Canada: Montréal*;* 2010.

[6] Toussaint K, Pouliot N, Montambault S. Transmission Line Maintenance Robots Capable of Crossing Obstacles: State-of-the-Art Review and Challenges Ahead. *Journal of Field Robotics* 2009; **26 (5)**:477–99.

[7] Montambault S, Côté J, St-Louis M. Preliminary results on the development of a teleoperated compact trolley for live-line working. *9th International Conference on Transmission and Distribution Construction, Operation and Live-Line Maintenance* (ESMO), Canada: Montréal; 2000, p. 21–27

[8] Montambault S, Pouliot N. The HQ LineROVer: Contributing to Innovation in Transmission Line Maintenance. *In Proceedings of the 10th International Conference on Transmission and Distribution Construction and Live Line Maintenance (ESMO)*. FL:Orlando; 2003, p. 33–40

[9] Pouliot N, Montambault S, Lepage M. Remote-controlled vehicle which travels on conductors and which can pass over obstacles by means of temporary support rotors. *PCT-Patent application WO 2004/070902 A1: World Intellectual Property Organization*, Applicant: Hydro-Quebec.

[10] Montambault S, Pouliot N. Design and validation of a mobile robot for power line inspection and maintenance. *In Proceedings of the 6th International Conference on Field and Service Robotics.* France: Chamonix; 2007.

[11] Montambault S, Pouliot N, Lepage M, Michaud J, Latullipe C, Comte C. Remote-controlled vehicle designed to be mounted on a support and capable of clearing obstacle. *PCT-Patent application, WO 2005/101600 A1: World Intellectual Property Organization*, Applicant: Hydro-Quebec.

[12] Montambault S, Pouliot N. LineScout Technology: Development of an Inspection Robot Capable of Clearing Obstacles While Operating on a Live Line. *In Proceedings of the IEEE International Conference on Transmission and Distribution Construction and Live Line Maintenance* (ESMO), NM: Albuquerque; 2006.

[13] Montambault S, Pouliot N. Inspection Robot Capable of Clearing Obstacles While Operating on a Live Line. *Electricity Today*, 2008, p.10-12.

[14] Pouliot N, Montambault S. Geometric design of the LineScout, a Teleoperated Robot for Power Line Inspection and Maintenance. *In Proceedings of the IEEE International Conference on Robotics and Automation*, Canada: Pasadena; 2008, p. 3970–3977

[15] Transmission Technology Roadmap – Pathways to BC´s Future Grid. *BC Transmission Corporation.* September 2008.

[16] Toth J, Pouliot N, Montambault S. Field Experiences Using LineScout Technology on Large BC Transmission Crossings. *1st International Conference on Applied Robotics for the Power Industry*, Canada: Montréal; 2010.

[17] Debenest P, Guarnieri M. Expliner – From Prototype Towards a Practical Robot for Inspection of High-Voltage Lines. *1st International Conference on Applied Robotics for the Power Industry*, Canada:Montréal; 2010.

[18] http://research.ict.csiro.au/

[19] http://www.arcaa.aero/

[20] Hrabar S, Merz T, Frousheger D. Development of an Autonomous Helicopter Aerial Powerline Inspections. *1st International Conference on Applied Robotics for the Power Industry*, , Canada:Montréal; 2010.

[21] http://www.landseerllc.com/landseerpage10

[22] Hrabar S. 3D Path Planning and Stereo-based Obstacle Avoidance for Rotorcraft UAVs. *IEEE/RSJ International Conference on Intelligent Robots and Systems*, France:Nice; 2008.

[23] Campoy P, Correa J, Mondragon I, Martinez C, Olivares M, Mejias L. Artieda J. Computer Vision Onboard UAVs for Civilian Tasks. *Journal of Intelligent Systems*, 2009; **54**:105–135

[24] Toth J, Gilpin-Jackson A. Smart View for a Smart Grid – Unmanned Aerial Vehicles for Transmission Lines. *1st International Conference on Applied Robotics for the Power Industry*, Canada: Montréal; 2010.

[25] www.pdghelicopters.com.