

# Expliner – Toward a Practical Robot for Inspection of High-Voltage Lines

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**Abstract** Preventive maintenance of high-voltage transmission power lines is a dangerous task, but the obstacles mounted on the lines have so far prevented the automation of this task. Expliner aims to overcome such obstacles by controlling actively the position of its center of mass, thus changing its configuration as needed when moving on the power lines. This work presents the design of Expliner and results of field experiments performed with very high voltages to prove the effectiveness of the proposed concept.

## Introduction

Urban centers and industries rely heavily on electric energy provided by an electric grid. This electric energy is needed for safety, transportation, sanitation and other essential functions. If there is any problem in the electric grid linking the energy generation plants and urban or industrial centers, the supply of energy may have to be stopped, affecting in a negative way the lives of millions of people [1]. In order to avoid such problems, the preventive maintenance of electric power lines is of vital importance. However, this is a very dangerous and time-demanding job, requiring specialized people to walk on the lines, suspended several tens of meters above the ground in remote areas like mountains and deserts. In addition, usually the energy supply must be interrupted momentarily for such inspections.

There have been proposals to carry on the inspection of power lines in more efficient ways. One involves the use of helicopters to check visually the conditions of the cables [2]. However, even in the case of remotely controlled helicopters [3], it may be dangerous to fly close to power lines, and the visual inspection will provide images of only the upper side of the cables. Another approach is to have people working directly on live lines with special gear to insulate them from the very high voltages [4]. This method requires good access to the cables from the ground, which may not be possible in mountains or other remote locations. In addition, it still depends on people moving on the cables, a risky operation.

In the field of robotics, several researchers have proposed machines for remote inspection of power lines. However, the presence of obstacles on the cables (such as cable spacers and clamp suspenders connected to the towers) makes the automation of this task more difficult. Campos et al. have proposed a machine to inspect the warning spheres installed on the high-voltage lines [5], but the machine is not able to overcome any sort of obstacle. Sawada et al. have proposed a robot with several degrees of freedom in order to cross clamp suspenders [6], but this resulted in a bulky and heavy machine that is difficult to carry to the field. Tang and Zhu have proposed a different machine that moves on the ground line, above the high voltage lines and with fewer obstacles [7][8]. However, the inspection performed with this machine is similar to the one with a helicopter, since only the upper side of the high voltage cables can be inspected with a video camera. Montambault and Pouliot are developing a very practical machine for inspection of single high-voltage lines [9][10], including the defrosting of frozen wires. In Japan, where the current research is being conducted, the high-voltage lines are grouped in bundles of four cables, and this presents different challenges that have not been solved in a satisfactory way until now.

## Proposal of Automation

Figure 1 shows Expliner, the machine proposed by the authors to perform remote inspection of high-voltage lines. Its mobility is based on pulleys, placed on

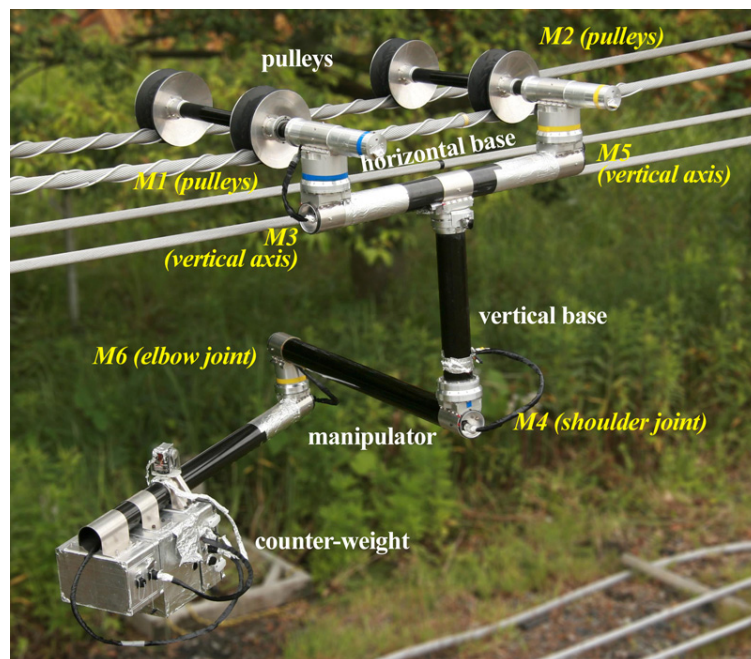


Fig. 1 – Concept of Expliner with main components.



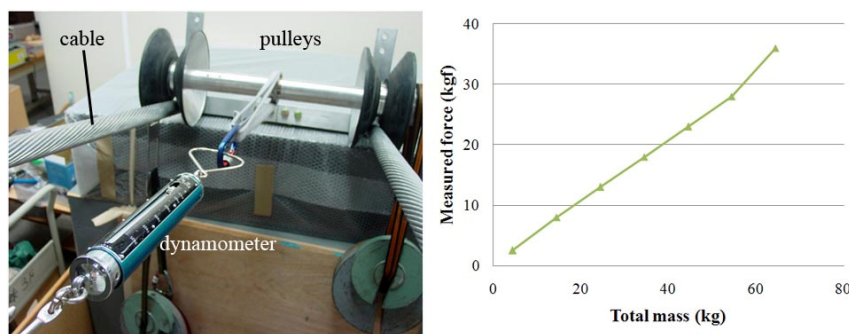
**Fig. 2 – Loading pipe between tower and cables (left) and clamp suspender (right).**

the upper cables, driven by electric motors. The pulley units are connected to a single horizontal base.

The horizontal base also has a vertical element, with a 2-DOF manipulator connected to its lower end. On the tip of the manipulator there is a counter-weight, housing batteries and electronics. Therefore, by moving the manipulator, it is possible to change the position of the center of mass of the machine. Thus, it becomes possible to lift one of the two pulley units in order to overcome large obstacles, as presented for the first time in [11].

If Expliner would move only in a straight line, it would be necessary to have only 1 degree of freedom in the manipulator. However, there are times when the machine must perform rather complex motions, such as when crossing clamp suspenders, or when moving on an inclined loading pipe between the tower and the main cables, as displayed in Figure 2. For such cases, not only the 2 DOFs of the manipulator are needed, but also the rotation around the vertical axis of each motion unit. These motions have already been described in [11].

The next sections will focus on the mechanical design of Expliner, and will also describe the main differences between the current machine and the first prototype, presented in [11].



**Fig. 3 – Friction experimental setup (left) and results from experiments (right).**

## Mechanical Design

### *Friction*

In order to dimension the actuators, it was necessary to determine the friction between the rubber-coated pulleys and the power cables. In spite of the theoretical models taking into account the deformation of the rubber around the contact area, the lack of friction data made it necessary to determine the friction empirically, by applying loads on the pulleys, mounted on the cables, and measuring the force required to pull them at a constant speed. The experimental setup and the data are displayed in Figure 3, and show that the pulling force is linearly proportional to the load applied on the pulleys, yielding a coefficient of friction that was used for the selection of the actuators.

### *Actuators*

All actuators were designed by the authors, so that the motors and transmissions be assembled in the most compact and effective way. In addition, the main components of Expliner can be assembled by sliding joints, which were also incorporated in the design of the cases of the actuators.

Each motion unit is equipped with a 200W brushless motor connected to a train of planetary gears with a total reduction ration of 60, maximum continuous torque of 40.4Nm and speed of 60.6rpm. With the pulleys of Expliner, this represents a linear speed of between 23m/min and 29m/min, depending on the size of the cables where the machine is moving.

The vertical axis of each motion units is powered by a 200W brushless motor with Harmonic-Drive reduction embedded in its case, resulting in a maximum continuous torque of 558.4Nm and 3.6rpm. The same actuator is used to drive the first joint of the manipulator (the “shoulder”), while the second joint (the “elbow”) is driven by a 200W brushless motor with embedded Harmonic-Drive, and with a maximum continuous torque of 349Nm and speed of 5.7rpm.

The dimensioning of the actuators of the manipulator took into account lifting the counter-weight when the manipulator is in a vertical configuration, something that does not happen in real applications, but which may happen during tests.

### *Structure*

The structure of Expliner is composed mainly of CFRP pipes, and they were designed to withstand the extreme postures required when overcoming obstacles.

In order to make Expliner easy to carry to the inspection sites, it was designed to be easily assembled with sliding joints and stopping pins, as shown in Figure 4. In places where the wiring might prevent an easy assembly, slide-in connectors were also employed.

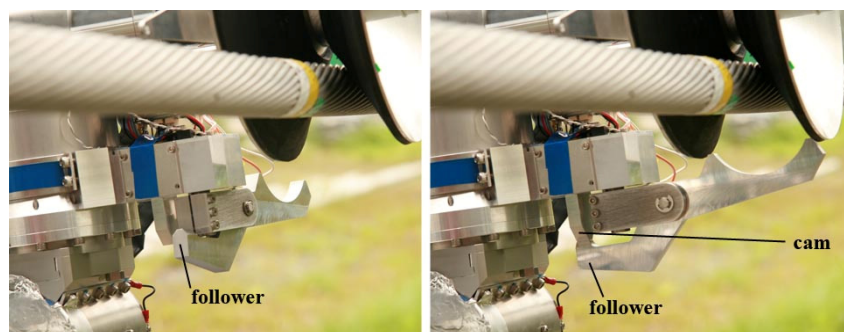


**Fig. 4 – Sliding joint for easy assembly.**

### *Safety Hooks*

Another improvement from the first prototype of Expliner was the introduction of the safety hooks, which keep the robot attached to the power lines even in case of sudden winds or accidents. The safety hooks must provide enough clearance to operate even with large loading pipes, but must be very close to the pulley in its engaged position to prevent the cable from sliding at the gap between hook and pulley. Therefore, the safety hooks were assembled with a cam mechanism that modifies the angle of the hook as it moves from the disengaged position (open) to the engaged position (closed), as shown in Figure 5. Each safety hook is driven by a worm-gear transmission, so it is self-locking.

It is necessary to disengage the safety hooks when crossing obstacles such as cable spacers or clamp suspenders, but also when moving on the loading pipe. Care is taken to insure that at all times at least one safety hook is engaged, so that



**Fig. 5 – Safety Hook disengaged (left) and engaged (right).**

Expliner would not fall from the cables in case of malfunctions or accidents.

The new version of Expliner is easier to assemble, easier to operate, and also lighter than the first prototype (60kg, against 85kg of the first version).

## Control Architecture

The control architecture has been greatly improved since the first prototype presented in [11]. Each actuator has its motor drive (HiBot TITech Drive Version 1) positioned close to it, in a splash-proof assembly. Communication between the motor drives and the main micro-controller, positioned in the counter-weight, was implemented with CAN bus.

By installing the motor drives close to the motors, wiring in the joints of the robot was greatly reduced and simplified. In addition, the entire machine is shielded for operation at very high voltages (500kV) and with high electric currents (1400A).

The counter-weight houses not only the main micro-controller (HiBot SH2Tiny), but also the wireless communication devices, which connect to a portable control station by wireless LAN. The wireless communication diagram is presented in Figure 6.

## Human-Machine Interface

Expliner is controlled from a portable control case shown in the lower right corner of Figure 6. From this control case it is possible to drive all joints independently, but this would result in cumbersome and time-demanding operations. Therefore, the obstacle-crossing motions were automated, but are always controlled by the operator, as described next.

When crossing a clamp suspender (Figure 7), the operator controls the position of the center of mass by moving a joystick forward or backward, while the two joints of the manipulator are driven automatically, so that the center of mass is always positioned between the two upper cables. Once the front motion unit is lifted with enough clearance from the cables, the operator starts the next step in the motion, which consists of rotating the front motion unit and bringing the pulleys out from the cables, while at the same time the position of the center of mass is automatically changed to accommodate for this change in posture. These motions are also achieved simply by moving a joystick forward or backward. Once this is completed, the operator moves the machine forward. When the front unit has passed the obstacle, it is brought back to its initial angle by a single joystick motion. Finally, when the front motion unit is aligned to the cables, the center of mass is brought back to the center position, which brings the front pulley unit back onto the cables. This process is then repeated to lift the rear motion unit.

All joints are driven in position control, with data from encoders. All motion patterns and limits are pre-defined, in order to make operation as fast and safe as possible. Therefore, the joints of Expliner will move until the defined angle, and will always go back to the initial postures with an accuracy of  $0.1^\circ$ .

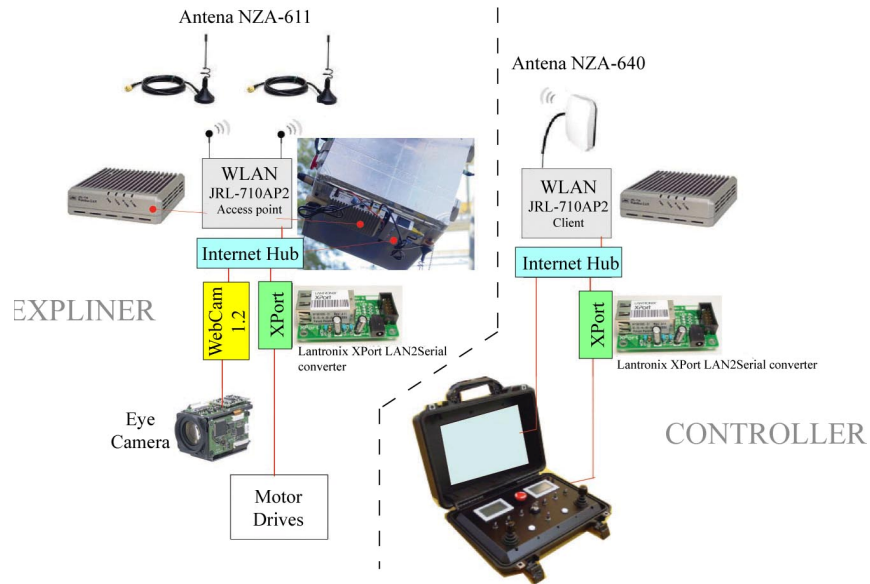


Fig. 6 – Wireless communication diagram

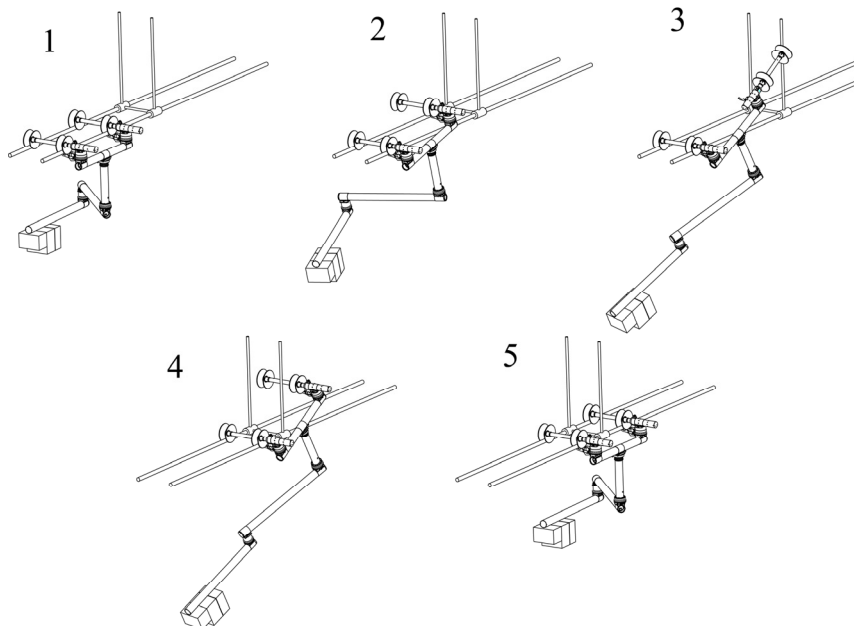


Fig. 7 – Sequence of motions for overcoming clamp suspender (first half of motion)

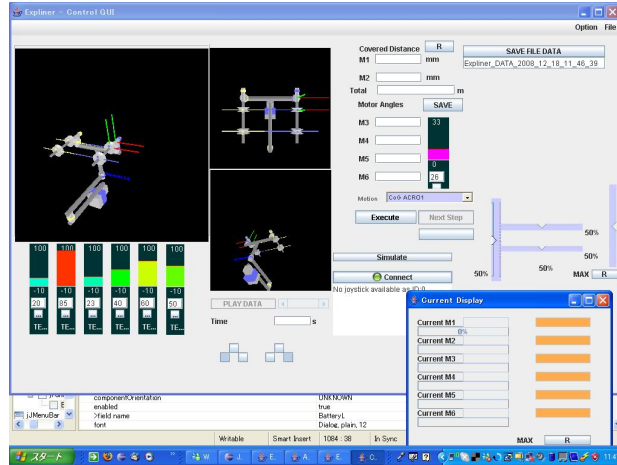


Fig. 8 – Graphic Interface with data from each actuator and other sensors.

Similar automated patterns have been implemented for other motions, such as moving between the loading pipe and the cables, so that the center of mass is always kept in a safe position. This automated control is especially useful when Expliner is moving on the single loading pipe. However, even with this level of automation, the presence of a human operator is always required due to the complexity of the environment.

The operator is always receiving telemetry data from the robot, including the temperature of each motor, the current consumption, the voltage level, the angle of each joint, and the attitude of the machine, with its spatial configuration. The graphical interface presented in Figure 8 makes the control of the machine more intuitive and easy to understand.

## Field Experiments

The latest prototype of Expliner has undergone intense field tests with very promising results. Speed tests performed on horizontal cables indicated an average speed of 27m/min, above the requirement of 20m/min. The required speed of 20m/min was set based on limitations in the sensors used to inspect the cables, which will be presented in the near future.

Expliner was also tested with all cable spacers used in West Japan (Figure 9), where it is supposed to be deployed. Additionally, Expliner was tested on inclined cables, with a maximum angle of 30 degrees, and even in such conditions was able to perform the obstacle crossing motion, as displayed in Figure 9.

Overcoming the clamp suspender and crossing to the other side of a tower was also verified in field experiments, as shown in Figure 10. The introduction of the automated control helped to reduce the time necessary to perform this motion, from around 12 minutes to approximately 3 minutes (with a trained operator).



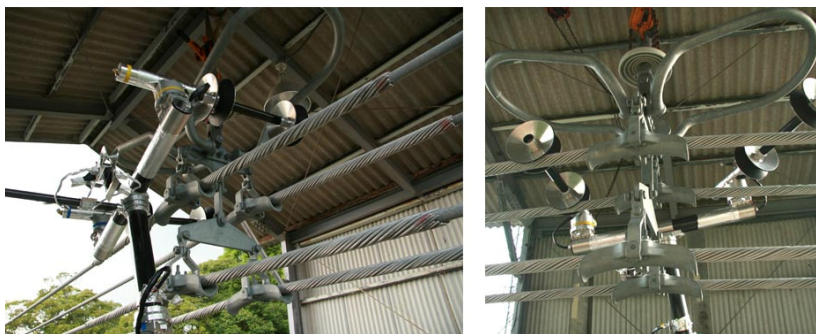
Finally, the motion on the single loading pipe and the transition motion between loading pipe and cable were confirmed in real field conditions, as shown in Figure 11. All tests were performed repeatedly on test cables and also on live wires with 500kV. In the latter case, footage obtained with a ultra-violet camera revealed the existence of a corona around the robot, but no malfunction was observed, thus proving the effectiveness of the shielding.

## Conclusions

With the development of Expliner, the automation of inspection of high voltage power lines became one step closer to reality. The field tests presented in this paper showed that the concept of changing the position of the center of mass of the machine can be employed in dangerous and complex applications such as power lines suspended tens of meters above the ground. The developments in human-machine interface and the automation of complex motions have made the control of the machine faster and more reliable. The deployment of sensors to acquire data from the power lines is a future step, but the authors are already working on it, and



**Fig. 9 – Cable spacers (left) and Expliner crossing obstacle on inclined cable (right).**



**Fig. 10 – Expliner lifting the front motion unit (left) and rotating the motion unit after crossing the clamp suspender (right).**



**Fig. 11 – Expliner moving on loading pipe (left) and performing an automated motion.**

plan to present concrete results in the near future.

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