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Expliner – Robot for Inspection of Transmission Lines

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***Abstract*— The inspection of high-voltage transmission lines is a dangerous and time-consuming job, that relies on especially trained workers operating tens of meters above the ground, and close to live lines with thousands of volts. This paper presents the development of a tele-operated robot designed for preventive maintenance of high-voltage lines. The robot was designed with mobility in mind, so that cable spacers, suspension clamps and other obstacles, which so far have prevented the use of robots for inspection of high-voltage lines, would not hamper the operation of the machine. After careful considerations on mobility, the robot was designed, and a prototype was built. Results of tests, performed on facilities reproducing real field conditions, are also presented in this paper.**

I. Introduction

THE high-voltage transmission lines connecting electric energy production facilities to large urban centers are vital elements of electrical infrastructure. Any failure in such lines may bring severe consequences to people's daily lives, affecting transportation, health, security and sanitation, to mention just a few. Therefore, the proper maintenance of high-voltage transmission lines is of extreme importance.

Preventive maintenance of the lines aims at detecting damages in the case or in the core of the cables, and requires people to walk on the lines – a time-consuming and dangerous job, in spite of all the safety procedures applied. In addition, when the lines are being inspected, the transmission of electricity must be temporarily suspended, which means that other lines may be overcharged in order to compensate for the line that is undergoing maintenance.

It is essential that preventive maintenance of high-voltage transmission lines be carried out in a safer and more efficient way, ideally without requiring the interruption of the electric energy supply. However, previous attempts to automate this task have been hampered by the spacers, suspension clamps and other devices installed on the lines, which represent formidable obstacles that need to be overcome tens of meters above the ground. High mobility is required in order to negotiate such obstacles.

This paper presents the first stage in the development of Expliner, a robot designed for remote inspection of powered high-voltage transmission lines. The basic concept of Expliner will be introduced, as well as its mechanical design and control system. The validity of the proposed concept will be confirmed with results of experiments, discussed in the end of this paper.

The sensors used for the inspection of the lines, as well as the mechanism for positioning the sensors close to the lines, will be presented in a future paper due to patent issues.

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II. Inspection of Transmission Lines

High-voltage transmission lines are usually arranged in bundles of 2, 4 or more wires, supported by transmission towers. The distance between the towers is usually between 300m and 500m, and they may be located inside forests, on mountains and in other isolated places. The suspended transmission lines are often composed of a metallic core and metallic casing. When exposed to the elements, the lines may suffer from corrosion, damages by lightning bolts, or even rupture of the core. In order to inspect the lines, workers must walk on the lines, in many cases suspended 100m above the ground (see Figure 1). Special gondolas may also be employed, allowing the operator to "slide" on the cables. These methods imply the interruption of transmission of electricity, require skilled workers, and expose the workers to unnecessary levels of danger and stress.

One option to this method is to carry out visual inspection of the cables by helicopter with video cameras [1]. Pattern-recognition algorithms may be used to improve the efficiency of inspection by video [2]. However, these inspection tasks tend to be expensive, and often provide just partial images of the cables. Flying helicopters close to the transmission lines and towers also involves risks that should

Fig. 1. Worker performing preventive maintenance on transmission lines, suspended tens of meters above the ground.

be avoided. Some of these risks may be reduced by employing unmanned helicopters [3]. Visual inspection from the ground is sometimes performed, but with very limited results. As alternatives to visual inspection, thermal sensing [4], X-ray [5] and electric sensing [6] can be used to detect damages in the transmission lines, but the sensors need to be positioned very close to the cables.

In the span between the towers, spacers are placed to keep the distance between the cables and avoid them from touching each other when the wind blows. Spacers may come in different shapes, and their bolts also need to be inspected from time to time (Figure 2(a)). In addition, the transmission lines are supported from the top by vertical structures consisting of insulators, connected to the towers. Suspension clamps are used to connect the lines to the insulators (Figure 2(b)). The maintenance of these structures is easier because they are located on the towers, but a detailed inspection would still require the interruption of electricity transmission.

A. Attempts to Automate the Inspection Tasks

The automation of inspection of transmission lines has often been hampered by the presence of spacers and suspension clamps ([7], [8], [9]), mentioned before. In order to overcome such obstacles tens of meters above the ground, any machine would need a high degree of mobility and reliability. One example is shown in [10], which consists of a robot with a foldable rail to overcome the towers. Another example is presented in [11], composed of 11 degrees of freedom and three arms to negotiate obstacles.

However, high mobility usually implies heavy and complex mechanisms, whereas a machine for inspection of transmission lines should be easy to transport (compact and lightweight), easy to assemble and reliable.

One point that most of the previous works have in common is that the robots move on the ground cable, located several meters above the transmission lines, and supported on the tops of the towers. Therefore, detailed inspection of the transmission lines, when possible, would require powerful cameras and special attitude-control methods [12]. Ideally, the robot should move directly on the transmission lines for more detailed data acquisition.

For maintenance of transmission lines up to 33kV, ground-based, insulated and tele-operated booms are employed, ([13], [14]). However, for high-voltage lines, the ground is not always available (in mountains or forests, for example), the lines are too high to be reached by booms, and insulation may not be feasible for extremely-high voltage lines.

(a) (b)

Fig. 2. Cable spacer (left) and suspension clamp (right).

B. Requirements for Automation

This work is being carried out in conjunction with Kansai Electric Power Corp. (KEPCO, Japan) and Japan Power Systems Corp. (JPS). Therefore, many of the requirements for the robot presented next apply to the Japanese high-voltage transmission lines. However, these details do not prevent the concept described in this paper from being adapted to operate with transmission lines of different dimensions or configurations.

Requirements (motion on transmission lines):

- distance between cables: between 400mm and 500mm
- diameter of cables: from ϕ24mm to ϕ48mm
- voltage levels: up to 500kV
- portability (high-voltage towers may be located in remote areas, in mountains or inside forests. All the parts of the robot must be portable and easy to carry)
- mass: within 60kg
- time of operation: at least 8h, continuous
- speed: 20m/min
- maximum inclination of cable: 30 degrees

Types of operation:

- Running on high-voltage cables;
- Overcoming spacers in a safe and quick manner;
- Overcoming suspension clamps without touching the structure or the tower;

Reaching the transmission line from an access cable – it may be necessary to assemble the robot on an access cable connected to the tower. When moving from the access cable to the transmission lines, the robot will need to change lines in a safe way.

III. PROPOSAL FOR AUTOMATION

A. Basic Concept

Initially, snake-like robots [15], or robots that move like inch-worms were considered for this application, but it soon became clear that they would be too complex and slow. In addition, transmission lines are unstructured environments, where robots would be exposed to changes in weather and obstacles in several different configurations. A more robust approach had to be sought.

For this purpose, mobility by controlling the center of mass of the robot was proposed. This concept had already been employed in different robots based on crawlers for moving loads on slopes [16]. However, for inspection of transmission lines, the robot would need at least two supporting points and one counter-weight (Figure 3). By moving the counter-weight, it is possible to change the position of the center of mass, and thus lift one of the supporting points.

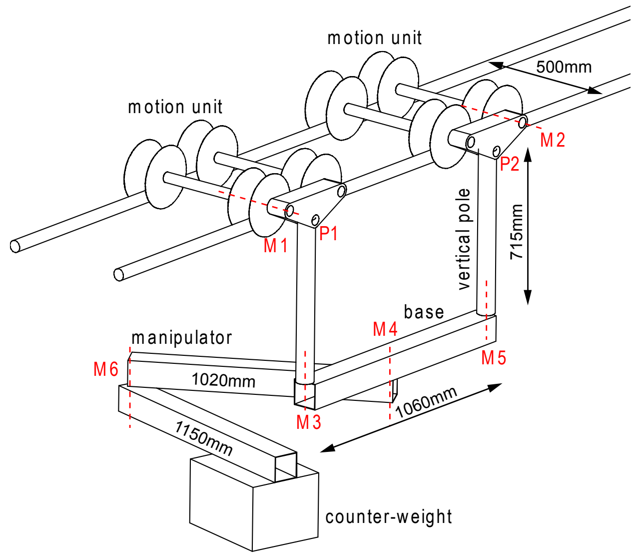

Fig. 3. Overall view of Expliner and its components

To keep the stability of the robot when moving on the lines, the center of mass must be positioned as low as possible, ideally under the lower transmission lines of the bundle of conductor cables. Therefore, the supporting points must be united to the base by vertical poles. The counter-weight is also connected to the base by a mechanism that changes its position, as shown in Figure 3.

This degree of mobility would be enough for overcoming spacers on the cables, but crossing the suspension clamps demands even higher mobility (Figure 4). In fact, when crossing a suspension clamp, each supporting point must be lifted once, rotated outside the cables, and then placed back on the cables after overcoming the obstacle, as depicted in Figure 4. This operation demands one degree of freedom (rotation) in each vertical pole linking the supporting point to the base. In order to control the position of the counter-weight of the robot when it is not aligned to the cables, 2 additional degrees of freedom are needed.

Therefore, the robot should be composed of two supporting points, composed of pulleys that move on the transmission lines. Each supporting point (named "motion unit") is equipped with one motor for motion on the cables (M1 and M2 in Fig. 3). Each motion unit is connected by a passive rotary joint (P1 and P2) to a vertical pole, which can rotate with respect to a common base (M3 and M5 in Fig. 3).

This base supports a 2-DOF planar manipulator (actuators M4 and M6 in Fig. 3), on the end of which there is a counter-weight, housing the batteries and electronics of the robot.

B. Acrobatic Modes

The process of overcoming suspension clamps was briefly mentioned before. This sequence of motions, in which the robot is at times supported by only one motion unit, is called "Acrobatic Mode 1", and is shown in Figure 4.

In order to prevent interruptions in the transmission of electricity, it may be necessary to assemble the robot on the tower and drive it to the transmission lines by an access cable. In this case, the robot will have to move on a single cable by controlling the position of its center of mass (Fig. 5-1). When reaching the lines, the front motion unit will be lifted (Fig. 5-2) and rotated to be aligned to the lines (Fig. 5-3). The robot moves forward, and brings the front motion unit down in contact with the lines by changing its center of mass (Fig. 5-4). Then, the rear motion unit is lifted, rotated, and the robot moves forward on the transmission lines (Fig. 5-5), supported only by the front motion unit. Finally, the rear motion unit is aligned to the cables, and it can be brought back down in contact with the lines (Fig. 5-6). The robot is then ready to conduct the inspection of the transmission lines, having its two motion units mounted on them. The entire sequence is

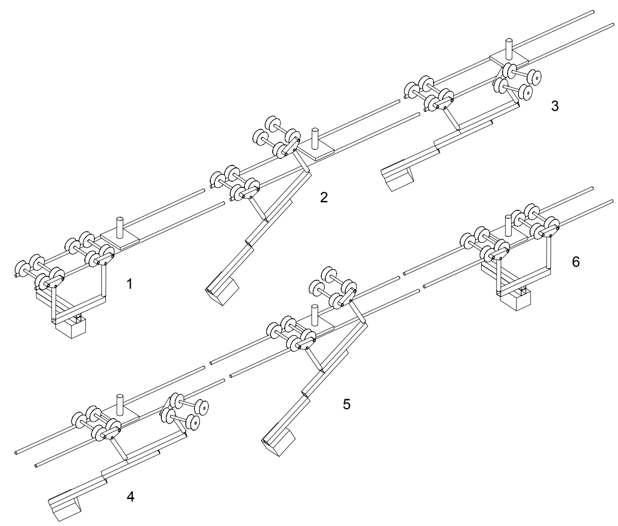

Fig. 4. Robot overcoming a suspension clamp.

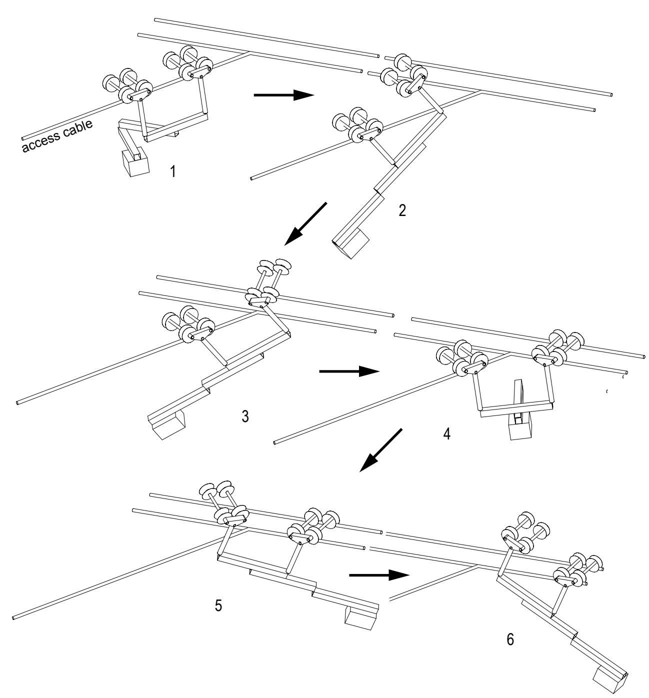

Fig. 5. Sequence of motion for "Acrobatic Mode 2".

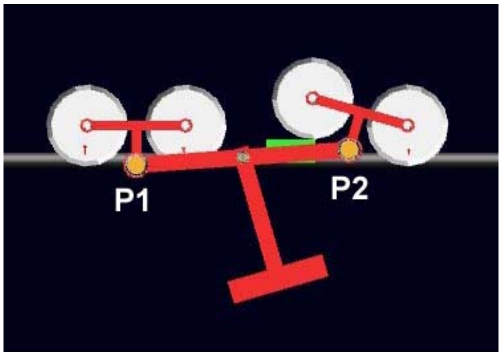

Fig. 6. Simulations of the motion unit with ADAMS. The right motion unit is climbing over a representation of a cable spacer.

called "Acrobatic Mode 2".

C. Simulations

Each motion unit should be composed of at least one shaft with two pulleys, for moving over a pair of transmission lines. The distance between the pulleys must be configurable, so that the robot can operate on bundles of lines of different specifications.

However, simulations performed with ADAMS® revealed that, when overcoming spacers on the lines, the motion of the robot would be greatly improved if there were two shafts in each motion unit. Therefore, when one of the shafts is climbing an obstacle (and momentarily losing traction), the other shaft is still in contact with the cable and is able to drive the robot forward. This feature is especially useful when one of the motion units is lifted for overcoming large obstacles.

As for the shape of the motion units, several configurations have been simulated with ADAMS®. Taking into account dynamic effects, the configuration that presented the best results is displayed in Figure 6. The two shafts are in the upper part of the motion unit, and the connection point with the vertical pole (a passive rotation joint, P1 or P2) is in a lower position, between the shafts.

The acrobatic modes introduced before have also been simulated. The necessary mass in the counter-weight to lift the robot in different configurations was confirmed, as well as unstable positions in which the robot would fall from the lines. The simulations provided valuable data that were used when testing the prototype and calibrating the positions of the counter-weight for the performance of the acrobatic modes.

IV. EXPLINER – MECHANICAL DESIGN

A. Motion Units

The motion unit consists of two shafts, each with two pulleys. A DC motor is embedded in one of the pulley shafts. The torque is then transmitted to the other pulley shaft by a timing belt.

The inner structure of the motion unit is composed of aluminum plates that form a cell. The structure is lightweight, has enough structural strength, and is relatively simple to build.

The pulleys are made of aluminum plates bent to the desired shape by pressing, and coated with conductive rubber. If normal rubber were used, it would function as a layer of insulation, resulting in the formation or electric arcs between the lines and the metallic body of the robot. To avoid this problem, the entire robot is kept at the same voltage of the transmission lines.

Each vertical pole is made of an aluminum pipe, connected to the motion unit by a passive revolution joints (P1 or P2 in Fig. 7), and to the base of the robot by an active revolution joint (M3 or M5 in Fig. 7). The vertical pole can be easily connected or disconnected to the motion unit by a pin, and to the base by a locking mechanism.

B. Base

The base of the robot houses the actuators of the vertical poles, as well as of the first link of the counter-weight manipulator (see Fig. 7). To drive each vertical pole, a geared DC motor of 150W is connected to a Harmonic-Drive transmission, providing a maximum continuous torque of 216Nm. High torque may be necessary especially when performing the Acrobatic Modes 1 and 2 on inclined cables, when the entire robot is supported by only one motion unit.

Every actuator is equipped with an encoder, so that the posture of the robot is always known. With the reference of the values of the encoders, it is possible to perform complex sequences of motion, such as the Acrobatic modes, in a simple way, with no need for complex calculations, as required in some other robots.

The actuator of the first link of the manipulator is similar to the ones used to drive the vertical poles, with a maximum continuous torque of 372Nm.

C. Manipulator and Counter-Weight

The counter-weight must be placed as far as possible from the base of the manipulator in order to maximize its influence over the position of the center of mass of the robot. However, this requires the actuators of the manipulator to be powerful and relatively heavy if compared to the other components of

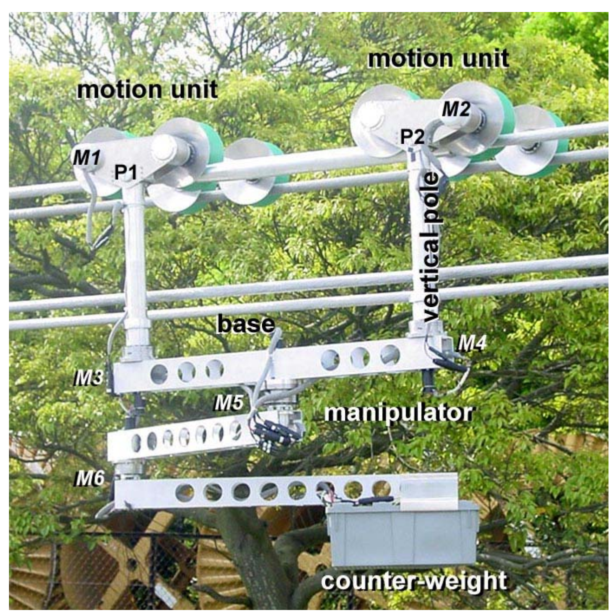

Fig. 7. Expliner and its sub-assemblies.

the robot.

The manipulator is composed of two links, with actuators located at its base (“shoulder joint”) and between the two links (“elbow joint”). The links can be quickly connected or disconnected by means of shafts with transversal safety pins, employed to lock the links of the manipulator in place. When the manipulator is fully extended, it has a reach of 2m. In order to move the counter-weight, located at the tip of the manipulator, the actuator of the “elbow joint” can provide a maximum continuous torque of 216Nm.

The counter-weight is composed of three sealed boxes, containing respectively the batteries, the electronics associated with sensing and data acquisition, and the CPU and motor drives. The latter box contains also the antennas and circuitry for wireless communication with the control unit. The total mass of the counter-weight is 25kg. The total mass of the robot (counter-weight included) is 84kg.

V. EXPLINER – CONTROL SYSTEM

Expliner can be controlled in semi-automatic mode, which means the user is always in charge of the operation, but does not need to control every single detail. In other words, when Expliner is performing the Acrobatic modes, the user simply authorizes the execution of the steps, but does not need to drive the manipulator and vertical poles to the correct, pre-defined positions. Those positions are stored in the memory of the controller.

A higher degree of autonomy can be achieved when the robot is simply moving over the transmission lines and acquiring data for preventive maintenance. However, complete autonomous control for the entire process is unrealistic in the current stage, due to the unstructured environment and the variety of spacers and obstacles that need to be crossed.

The following subsections describe the portable control unit for Expliner and the wireless communication system, as presented in Figure 8.

A. Portable Control Unit

The portable control unit was implemented with a tablet notebook, a panel with switches and joysticks, antennas for wireless communication, batteries and the associated circuitry, assembled inside a robust and compact case. The entire assembly is dust-proof and splash-proof, and has been extensively tested in outdoor environments.

The notebook may display the current configuration of Expliner with data from its encoders, and provides additional information to help the user control the robot, such as images from cameras.

B. Wireless Communication

The communication system is based on wireless LAN TCP/IP protocol. The WiFi bridge is made between the control box and the robot CPU Box. The access point of the robot is made by installing a wireless LAN JRL-710AP2 station in the CPU Box. The 10/100 Base T port is connected to a normal network hub. From the hub, a LAN line goes to a

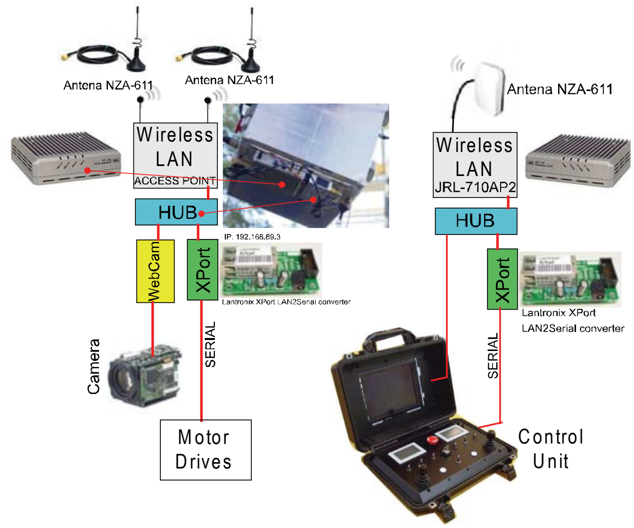

Fig. 8. Portab;e Control Unit (right) and Wireless Communication diagram of Expliner

Lantronix XPort LAN to serial converter.

On the control unit side, another wireless LAN JRL-710AP2 is utilized for the wireless connection to the robot. The XPort device receives in input the command from the Joystick of the control box by Serial (TTL level) communication and copies in output the same input command in LAN TCP/IP communication.

Implementing a reliable, long-distance wireless communication system can be very tricky due to the restrictions in power usage and the limited angular range of the antennas. With the system described above, it was possible to establish stable wireless communication over 200m away from the robot, provided the robot is in clear view from the control unit.

VI. FIELD EXPERIMENTS

Several experiments have been performed between 2005 and 2006 in test facilities that reproduce the conditions that the robot is expected to face when running on transmission lines. The results are briefly described next.

A. Results of Experiments

Speed: Expliner was able to move on the test lines at 40m/min, twice the speed specified in the requirements;

Line spacers: all cable spacers currently in use in the high-voltage lines of western Japan were successfully overcome. One type of spacer requires Expliner to shift its center of mass to pass it. All other spacers were overcome without the need to change the center of mass (Fig. 9);

Acrobatic mode 1: the sequence of motions was mapped and the data of the encoders were input in the memory of the controller. Even an operator with limited experience can control Expliner in semi-automatic mode when performing Acrobatic mode 1 (Fig. 10);

Fig. 9. Motion unit of Expliner overcoming four different cable spacers

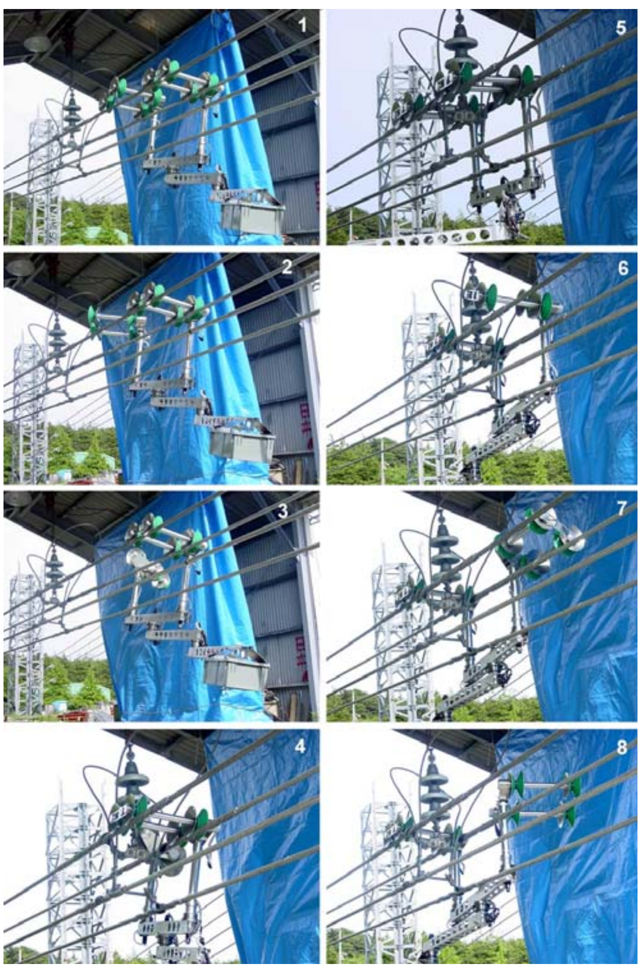

Fig. 10. Sequence of pictures of Acrobatic Mode 1

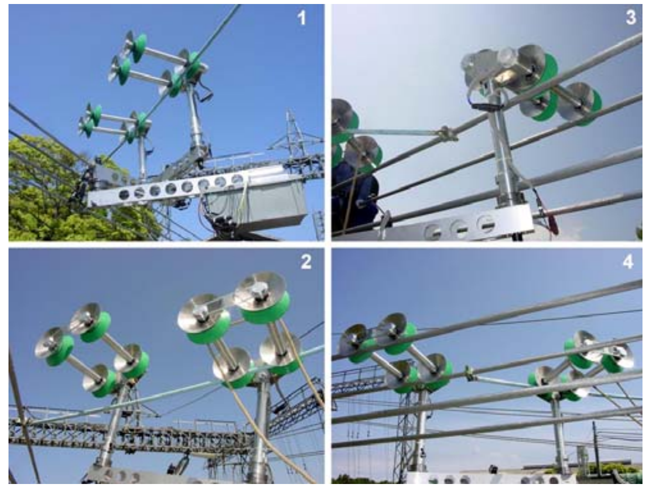

Fig. 11. Sequence of pictures of Acrobatic Mode 2 (1: moving on access cable; 2: lifting front motion unit; 3: aligning front motion unit with power lines; 4: placing fron motion unit on power lines)

Acrobatic mode 2: the sequence of motions has been performed in several different configurations (Fig. 11), and an optimum configuration of the access cable (length, angle with transmission line and height) has been identified. The performance of Acrobatic mode 2 in semi-automatic control requires more intermediate points than for Acrobatic mode 1, and the authors are working in its implementation;

Operation on inclined cables: Expliner was able to climb cables with an inclination of up to 30 degrees (Fig. 12). However, the motion units were dragging more electric current than the recommended limit to operate continuously. In addition, overcoming spacers on inclined cables requires Expliner to change its center of mass. One type of spacer could not be overcome. Finally, Acrobatic modes 1 and 2 could not be performed on inclined cables because the robot is not able to tilt its front motion unit enough.

Slippage of the wheels against the power lines occurred in the first prototype of Expliner because the rubber coating of the wheels provided too little friction. The problem was corrected after modeling the forces involved in the rolling of the wheels against the inclined cables and defining the minimum coefficient of friction needed to avoid slippage.

B. Features to Be Improved

The transmission lines are always in catenaries, and the

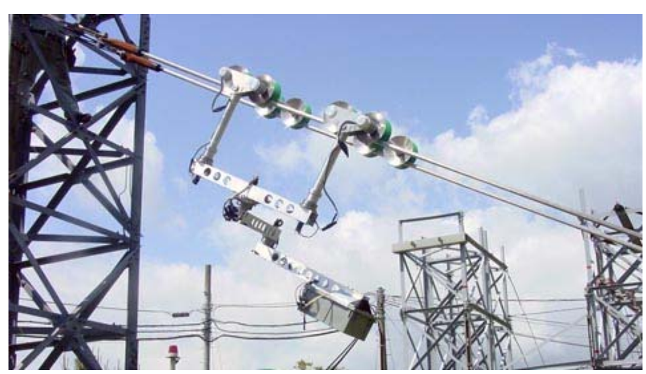

Fig. 12. Expliner moving on inclined cables (inclination: 30 degrees)

only part where the lines are horizontal is between the towers. Therefore, any practical robot must be able to perform obstacle avoidance on inclined lines. The current prototype could confirm its mobility concept on horizontal lines, but not on inclined cables. Therefore, its overall mass must be reduced, while concentrating mass in the counter-weight, so that the motion units can be lifted more and perform obstacle avoidance even on inclined cables.

The actuators of the motion units need to be redimensioned, so that they can operate continuously even when climbing inclined lines. One option may be to trade speed for torque. Since Expliner is able to move twice as fast as required (40m/min, against the requirement of 20m/min), a higher reduction ratio in the actuators of the motion units may provide the additional torque needed to climb inclined cables without excessive current consumption.

To avoid accidents, a safety device must be installed on the robot to prevent falls from the transmission lines or access cable in cases of sudden strong winds or loss of control.

Finally, the effects of operating the robot on 500kV lines, such as interference with the wireless communication caused by the strong electro-magnetic field, and current leakage, must be thoroughly analyzed.

VII. Conclusion

Expliner is under development as a robot for remote inspection of high-voltage lines. By controlling the position of its center of mass, it presents enough mobility to overcome the obstacles that often prevent other machines from moving on transmission lines. Even though there are several features that need to be improved prior to its deployment in real transmission lines, the results of experiments so far suggest that a version for real operation may be ready in the near future.

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