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ROBOTS FOR LIVE-POWER LINES: MAINTENANCE AND INSPECTION TASKS

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Abstract: This paper is focused on the robotic application for electrical live power lines maintenance. These tasks are matters of great significance for utilities companies, since their goal is to achieve a good quality of service. The main features of these works are that: the tasks are carried out over live-lines up to 90 kV; the robots are teleoperated by human operator; and a vehicle to place the robots over the desired line is required. In this paper the main development of teleoperated systems for live-line are mentioned, and the ROBTET system is described on detail. This telerobot has been developed by the Universidad Politéc. de Madrid, in collaboration with Iberdrola and Cobra, Spanish utility and contractor respectively. *Copyright 2002© IFAC*

Key words: teleoperation, telerobotics, live-power lines.

1. INTRODUCTION

The electrical sector plays an important role in the technological and industrial progress of a country, as we could see in California recently. Robotic systems have in this sector great possibilities of appliance (Parker 1999). In last decades, the fast growth of the industrialized countries has been possible due to the contribution of the utilities. These companies have an agreement with the industry to supply the demanded energy.

A potential task to be robotized is the live power line maintenance but till today only few prototypes have been developed and their application is restricted to those developing companies. Therefore, no commercial system is currently to be found on the market.

Live-power lines maintenance is characterized by three main features:

- Works can be carried out over power elements but in any case being in contact with elements of different power degree, like touching simustaneously two lines or a line and the tower
- The work environment can be previously known but not the elements positions and the relation among them.
- The task execution is conditioned by the tower and lines location, which normally is very complex. A proper vehicle for these tasks is therefore required.

The previous aspects determine the development of any telerobotic system. All proposed systems are based on teleoperated robots where the human operator monitors, in different degrees, the task execution. So this progress can be seen as a powerful tool that the sector workers can benefit from.

Taking into account previous features, the application of teleoperated robots on live power line maintenance showes the following advantages:

- Security and comfort increase for workers, since tasks are carried out by robots preventing workers from the risks involving the manipulation. Tasks are in distance monitored.

- Cost reduction in maintenance works. Teams of 4 to 5 members can be reduced to 2 or 3 people.
- Higher degree of standarization and systematitation of maintenance tasks since the programmed procedures for robots require determined steps for the right execution of maintenance tasks.

2. COMMON TASKS FOR LIVE-POWER LINES

The maintenance tasks on live-lines imply a limited risk despite the qualification of the workers. The risk appears when events occur unexpectedly. Next, common tasks to be carried out in electrical networks are shown:

- Change insulator sets
- Open and close switch
- Establish new connections
- Change the line equipment
- Inspect the line equipment

All these types of tasks are executed manually by high qualified workers. They employ techniques that have been widely studied and developed in order to avoid the risk of the worker, and also to increase the efficiency and minimize the execution time of the task. The two widely spread techniques used in manual live line maintenance are:

- Distance works (working indirectly)
- Potential works (working directly)

In the first technique, the worker manipulates the line using different kinds of insulated hot-sticks. The operator works close to the line, tying up to the pole and perfectly insulated.

By using the second technique, the workers remain in touch with the line, covering previously some areas with insulated accessories in order to prevent electrical shock and touching different elements of the line with proper rubber gloves. This technique can also be done with the worker in an insulated bucket placed on the top of a boom and close to the line.

Some other techniques include the use of helicopters to hold the bucket with the worker inside and close to the line. This technique is quite expensive. Figure 1 shows workers using hot-sticks and working from a bucket.

The possibility of an outage-free maintenance of distribution and transport aerial lines (without interrupting the electric energy on the line) depends on the current legislation of each country. In Spain,

Fig. 1 *Indirect work (using hot-sticks) and direct work (from a bucket)*

it is possible to handle different maintenance tasks on the aerial lines without previously disconnect the energy. In some other countries, a total disconnection must be done before the worker starts his work. The risks associated with the maintenance task on hot lines are: electrical shock, the radiation of electromagnetic fields, and fall from the high working place. All these aspects have been widely studied in order to reduce the hazardous conditions of the worker. Moreover, in the last years these aspects have been improved by the adaptation of a new technology: the teleoperation. This new technology may eliminate the risk of electric shock, falls, and also increase the comfort of the worker during the maintenance tasks. The ROBTET system described in this paper is a Spanish solution for the hot line maintenance using the teleoperation.

3. DEVELOPED SYSTEMS FOR LIVE-POWER LINES

Since the 80's, the electrical sector introduced the teleoperation technology to develop new procedures for the maintenance tasks on aerial transport and distribution lines. Some interesting semiautomatic robotic systems have been designed around the world.

Countries as USA, Japan, France, Canada and Spain, have been developed telerobotic prototypes for this tasks. Most of them are made up of robots which are teleoperated from a cabin on the ground or in the top of a boom close to the electrical line.

At the end of eighties Japan developed some telerobotics systems for live-power lines. These system was designed to operate in their distribution lines up to 6,6 kV. Aichi Inc. (Aichi 1993) develop in the early 90's a system with two hydraulic teleoperated robots. Robots are guided by the operator placed at the top of the boom. *Shikoku Electric Power Co.* developed a hydraulic arm controlled from a bucket on the top of a boom to execute maintenance tasks; the system incorporated an additional complete set of tools to support with the arm.

Kyushu Electric Power Co. (KEPCP) is the company with most robotic units in use for this purpose (Maruyama 1993, 1996, 2000). Among their systems deserves mentioning *Phase I* which includes two electric robots teleoperated by means of a joystick, from an aerial bucket placed on the top of a boom. At the end of 1993, they developed the *Phase II* system incorporating two robots teleoperated from a cabin on the deck of the vehicle. The system consists of several cameras located up to show the operator all the information related to the task's environment. There is also a man-machine interface with a touching panel display and a recognition voice system to control the movements of the cameras. The *Phase II* system incorporates a very useful device: the automatic tool changer (ATC). The latest research at KEPCO is focused in the system called *Phase III* system aiming of a fully automatic robot.

Since the middle of the 80's, the *Electric Power Research* Institute *(EPRI)* in the United States has been working in a system called *TOMCAT* (EPRI 1987). The first prototype consisted of a single hydraulic robot teleoperated from a cabin located on the ground. The system was designed to work with lines in a range from 50 kV up to 345 kV. The system is capable to work in very high aerial lines. The next stage in this system is the *TOMCAT 2000* with the possibility of developing live line maintenance tasks under freezing rain and darkness.

In *Canada*, the *Hydro-Quebec Research Institute* (Boyer 1994, y Coté 95), developed a system consisted of two hydraulics robots teleoperated from an aerial cabin placed on the top of a boom and an auxiliary arm capable of a very long acess. The system may operate in distribution lines of 25kV.

In France two projects for live-line maintenance have been started, but any result have been achieved until now. The first was supported by EDF at the 90's, but it was cancelled later (Soler 1993). At the end of 90's a consortium called TST 2000 was started, supported by the French Thomson-CSF and the Japanese Nissho-Iwai and Yaskawa.

4. ROBTET: TELEROBOTIC SYSTEM FOR THE NETWORK MAINTENANCE

The ROBTET has been designed to carry out maintenance tasks on the Spanish power supply network (up to 56 kV). All components are installed on a 4*4 truck with a power of 169 kW (230 HP) (Aracil 1993, 1995, 1998). It holds a hydraulic pump unit and an electric generator of 10 kW. Figure 2 shows a general view of the system.

Fig. 2 Insulator set change by the ROBTET

System works in a semi-automatic mode with the operator sending commands from the cabin on the truck, and receiving information from the remote working place. Telemanipulators and tools are placed on a remote platform located on an isolated telescopic boom. Although this configuration provides a completely safety conditions to the operator, it is also required to achieve the proper operator interaction with the remote working environment in order to obtain a useful teleoperated system. According to these requirements, two work places have been developed: the **operator's working site** placed on the cabin and the **remote working site** placed on the remote platform. Communication between both sites is done via optical fiber cable to guarantee the electrical isolation.

4.1 Operator's cabin

Operator's cabin contains the operator interface devices and the control computers. Operator interface devices have a double function: 1) to show the operator the status of the executing task and, 2) to send the operator's commands to the remote environment. The control computers process the information that flows between the operator interface and remote devices.

The operator interface is made up of the following devices:

- Two master arms,

- A stereoscopic display
- A multimedia display
- A microphone, and
- Several auxiliary devices

Fig. 3. Operator's cabin

The two master devices with force feedback developed by Kraft Telerobotics. The masters have 6 dof and are used to guide the manipulators and to reflect forces to the operator. The normal reflected forces are obtained by applying the measured torque of the slave joint actuators -reduced by a scale factor- through the corresponding joint motors of the master.

The stereoscopic display shows the images from the stereoscopic cameras placed on each slave manipulator. These cameras show detailed images and provide an excellent depth perception to the operator. The operator must use a proper glasses to see the stereoscopic images. The multimedia display shows a simple video image and information about the task. The video image is taken by the overall camera. It shows general and detailed images that provide to the operator the perception of the different elements at the remote working site.

The microphone is used to send the voice commands to the interface and also for the external communication via walkie-talkie. During the task performance, the words said by the operator are used to move the overall camera, to indicate the step of the procedure executed, to select the stereoscopic image shown on the stereoscopic display, and to enable or disable the external communication.

System computers are used to process the information exchanged between the operator and the remote site. A work stations and several specific computers are used to carry out different processes. They are described as follows:

- Multimedia work station
- Two telemanipulator controllers
- A voice recognition system
- A stereoscopic image generator
- A microcontroller

Multimedia work station. This computer shows a video image from the overall camera, a graphical simulation from the remote environment, a procedure list to be executed and several information about the current task and system state. This computer has the geometric model of the remote environment and all the system variables as positions, state, etc. Its main function is to evaluate the slaves position and reflect virtual forces to the master arm if the slave is inside a forbidden area. This environment model is calibrated by the operator and used by the computer at the graphical simulation.

Two telemanipulator controllers (KMC) developed by Kraft Telerobotics. The controller implements a bilateral control algorithm between the master device and slave manipulator. The slave is guided according to the master joint position. A force, proportional to the slave force generated during the manipulation, is fed back on the master device.

The voice recognition system acquires the words said by the operator and sends the corresponding command to the respected process. Voice commands are used to control the overall camera, the procedure steps, and to select the stereoscopic displayed image. A stereoscopic image generator developed by Stereographics. This computer processes the images sent by the selected stereoscopic image. The displayed images are synchronized with the operator's glasses in order to see the stereoscopic image.

4.2 Remote platform

The remote platform is located on the top of an isolated telescopic boom, as shown in figure 4. The platform has pan and tilt movements controlled by the pendant placed in the cabin. It holds two slave manipulators, an auxiliary jib, the overall camera, and tools. The communication between the platform and the cabin is carried out by several optic fiber cables inside the boom. The components are described as follows:

- Two slave manipulators
- Two stereoscopic video cameras
- A overall video camera
- An auxiliary jib

Two slave manipulators developed by Kraft Telerobotics. These are hydraulically powered and have 6 dof plus the grip action. The maximum

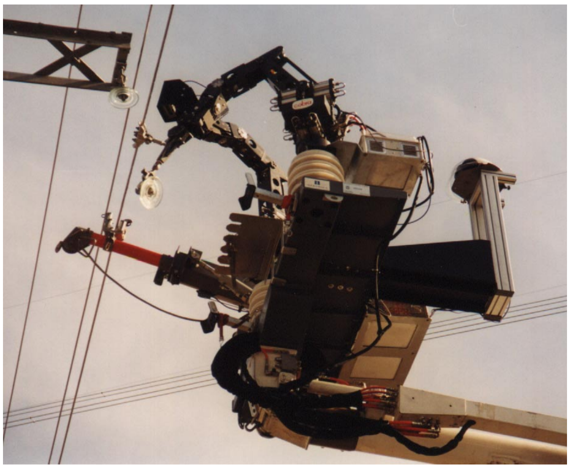


Fig. 4. remote working site

payload of each arm is 45 kg and the net weight 60 kg. Slaves are guided by the master movements and the torque of each joint is reflected on the master device. The manipulators have its own power supply for the communication and the stereoscopic cameras. They are mounted on special insulators in order to provide different potentials for each manipulator.

Two stereoscopic video cameras mounted on the end of each manipulator. The images are calibrated in order to obtain the best depth perception at 50 cm. This distance is the usual one to the parts manipulated by the slaves. A good depth perception has a great influence in the system productivity. The task execution time would increase significantly if the operator would not have a good spatial perception.

The overall video camera**.** It has three degrees of freedom: pan, tilt and zoom; all movements are controlled through operator voice commands. The camera is located behind the both slaves to have a good general view. From this point of view, the operator can see the manipulators as if they were his arms. This provides an excellent teleproprioception when the task is started. When he manipulates the hot line, he needs more detailed images. It is possible to use the zoom of this camera or the stereoscopic cameras.

The auxiliary jib is specially designed for the ROBTET, and constitutes a powerful tool for the telemanipulators. By using the jib, as shown in figure 4, the procedures have been simplified and the execution time has been reduced consequently.

Several tools are placed on a special box before starting up the task execution. Tools are adapted to be picked up by the manipulators. In some procedures, it is necessary to include new tools to facilitate some procedure steps. In these cases, new tools allow to reduce the time execution.

5. PROCEDURE EXECUTION AT THE ROBTET

The procedures for developing manual hot line maintenance tasks follows strict rules in order to prevent hazardous risks to the operator. Depending on the kind of task to implement on the line, a certain procedure must be applied.

The most frequently maintenance tasks to carry out in a distribution line are to change out an insulator set, to attach a jumper cable between two points of the line, to open switching units on the line and to replace fuse elements These works are performed by using the previously well-developed manual procedures for the direct work method. Two operators are required to execute a complete task. One of them will operate inside the cabin, control the platform, the boom and will perform the task; the other one has to carry out the corresponding steps outside the cabin and he is also a supervisor during the execution of the task, by informing to the operator.

Different suitable tools are needed to perform a task on the line. A specific tool box set was designed to place up to 6 different tools (extraction tool, insertion tool, etc) to use during the execution task. The tool box set is located in the aerial platform's base. All the tools are easily accessible for both robots.

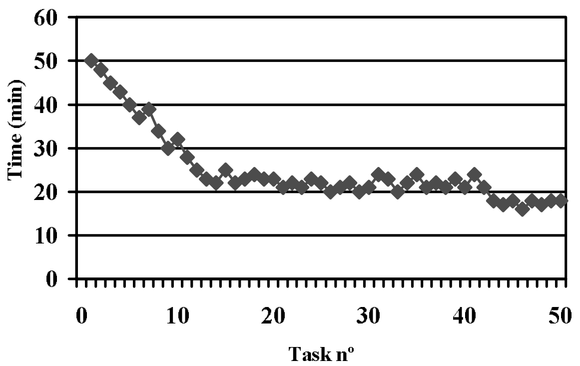
The following table describes step by step the proper procedure to change a plate placed in a vertical string. The operator of the ROBTET system must be a capable worker who previously had worked in outage-free maintenance of aerial lines; he also passed a training phase to familiarized with the ROBTET system.

Step	***Operation***
1	Place the platform at the proper position
2	Extract the clip of the line
3	Raise up the line using the jib
4	Extract the clip of the replaced plate
5	Raise down the line using the jib
6	Retire the plate
7	Place the plate in the material box
8	Insert the new plate
9	Introduce the clip into the new plate
10	Raise up the line by the jib
11	Insert the clip of the line
12	Retire the robots and the jib

6. OPERATOR TRAINNING

It is a very important fact to introduce a new system. Some points must be taken into account: operator´s interface must be friendly, computer starting up process have to run automatically, devices using by operator should be comfortable, and so on.

A lot of interesting information have been obtained from the training phase. Figure 9 shows a typical training evolution. Initially, the operators spent a lot of time because they need to get acquainted with the system. The dexterity in the use of the master devices increases gradually so the execution time is reduced. Finally, the interface is used skillfully and the time to execute the procedure remains around a final execution time. Usually it is necessary to repeat the procedure twenty times or more to reach the final execution time.



7. CONCLUSIONS

Telerobotic systems are been developing for outage-free maintenance tasks, technical and labor factors must been taken into consideration. New and better teleoperated systems for live-power lives should been promoted by the application of step forward in the fields of telerobotics, automatic tools, and object modeling and recognition.

These new telerobotics will be conceived like powerful tools for the electrical network workers. It will involve a breakthrough for the security and standardization in live-power line maintenance tasks.

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