

ADVANCED TELEOPERATED SYSTEM FOR LIVE POWER LINE MAINTENANCE

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Abstract

The teleoperated system ROBTET described in this paper, has been applied to live-line maintenance tasks since 1999. Manual outage-free maintenance of power lines suffer from potential hazards of electric shocks and falls from the working place during the task execution. Some of the technologies involved are: stereoscopic vision, voice commanded recognition, and virtual force reflection. They have been integrated in order to obtain a teleoperated system which is able to perform common live-line maintenance procedures. The advantages obtained by the ROBTET system in this field and experiences about operators' training are described in this paper.

Keywords: teleoperation, telerobotics, stereo vision, force reflection and telepresence.

1. INTRODUCTION

In outage-free maintenance procedures the workers have to do their job on a hot line, either indirectly by means of various kinds of hot-sticks or directly by touching the line with rubber-insulated gloves. Therefore, workers are compelled to work in a potential hazardous environment embracing both the risk of electric shocks and the danger of falling from a high place. In addition to that, they have to be very skilled and work cooperatively under very demanding conditions.

In this context, the electric utilities Iberdrola and Cobra and the research group Disam, have developed a telerobotic system called ROBTET (Aracil 1995,1996; Peñín 1998a). ROBTET consists of a truck with an operator's cabin on its base and a remote platform with several robotic devices and sensors placed on a telescopic boom. Other systems have been developed around the world (Epri, 1987; Maruyama 1993, 1996). After two years using the ROBTET, the main advantages observed in comparison with the manual procedures are:

- (1) minimizing failure probability and the consequences derived from the worker mistakes, which are extremely dangerous.
- (2) increasing the safety and comfort conditions of the operator, eliminating the need of being near or in contact with the live-lines.
- (3) eliminating the need of a continuous operator synchronizing and timing the tasks of the other workers, reducing its workload, and therefore upgrading his performance.
- (4) making control easier, standardizing the operational procedures, allowing the operator to give instructions referring himself only to objects and goals.

2. SYSTEM DESCRIPTION

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) (Santamaria 1997). It holds a hydraulic pump unit and an electric generator of 10 kW. Figure 1 shows a general view of the system.



Figure 1. General view of 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.

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 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.
- A **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 operator can only see one stereoscopic image from the two stereoscopic video cameras located at the slaves, therefore he may select the proper image.
- A **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 operator can also see a graphical simulation of the task and information about the executed step of the task procedure.



Figure 2 Operator's cabin

- A **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.
- Several **auxiliary devices** as pendant and alarms. The pendant is used to locate the remote platform near to the power line. The alarms inform about charge levels of the batteries and other anomalies of the power supply system.

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

- **Multimedia** work station developed by SGI. 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.
- **Sparc** work station with two processors developed by SUN Microsystems. 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 SGI 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.
- A **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.
- A **microcontroller** has been programmed to read and write the information between master and slave. This channel is used to read the slave position and to write virtual force to the master device.

Remote platform

The remote platform is located on the top of an isolated telescopic boom, as shown in figure 3. 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, tools, and isolated power supplies with an autonomy of 12 hours for the electronic components, as cameras and slaves communications. The communication between the platform and the cabin is carried out by several optic fiber cables inside the boom. The hydraulic power



Figure 3. remote working site

for manipulators and jib is taken from the truck using isolated oil and hoses. The components are described as follows:

- Two **slave manipulators** developed by Kraft Telerobotics. These are hydraulically powered and have 6 dof plus the grip action. The maximum 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 stereoscopic cameras provided two synchronized video signals. 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**. It is placed next to the right slave manipulator. It is hydraulic powered and has three dof: pan, tilt, and telescopic extension. The telescopic link is isolated up to 49 kV. Therefore, the jib can hold up the live-line while the manipulators are working at other potential. The jib is specially designed for the ROBTET, and constitutes a powerful tool for the telemanipulators. By using the jib, as shown in figure 3, 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. Before defining new procedures, it is necessary to study the used tools in order to obtain a performance similar to the manual execution.

Different configurations are possible to place the above devices, but several factors like power isolation and teleproprioception must be taken into account. Power isolation provides different potentials at the remote platform and therefore each slave can manipulate a different live-line. Operator's teleproprioception depends on the relation between operator commands and the result of his action on the display. So a movement to the right in the master should have the respective movement to right on the display, and so on. Operator's cabin and platform have a similar configuration, the overall camera is placed back to the manipulators in order to simulate the operator head position, and its image is shown on the graphical work station in front of him.

3. SYSTEM ARCHITECTURE

All computers and devices are linked in order to provide the operator to close the different control loops defined at the teleoperated system. Three senses are stimulated in the operator to inform him about the teleoperated task: vision through video cameras and graphics, touch through force feedback, and hearing to receive alarm information. Two ways are used by the operator to generate commands: hand

movements to guide manipulators, and voice to control overall camera and interface configuration. Computers have to process the different information channels in order to make easy the operator interaction. The system architecture has been designed to provide the operator with the maximum degree of telepresence. The main goal is to give the operator as much feeling of telepresence as possible in order to perform the teleoperated task in an easy and comfortable way. Under these conditions, the teleoperated system should be as powerful as the manual traditional system, and then it is possible to compare both by using other parameters like productivity, time execution, and safety. Figure 4 shows a diagram with the main devices and computers used at ROBTET.

The defined models of the task and the remote environment into the computers provide to implement teleoperation advanced help, as voice command generation, collision detection, virtual force reflection, and graphical simulation. Two

problems may appear when a computer model is used. First, the necessity to generate a model including useful information for the running process and secondly, the calibration of the computer virtual model with the real world.

The first problem is solved by using a model-based polyhedral elements. This model has to be defined before starting the work according to the type of tasks to be executed. It is assumed that all the geometric models of the intervening elements are known but the spatial location is undetermined.

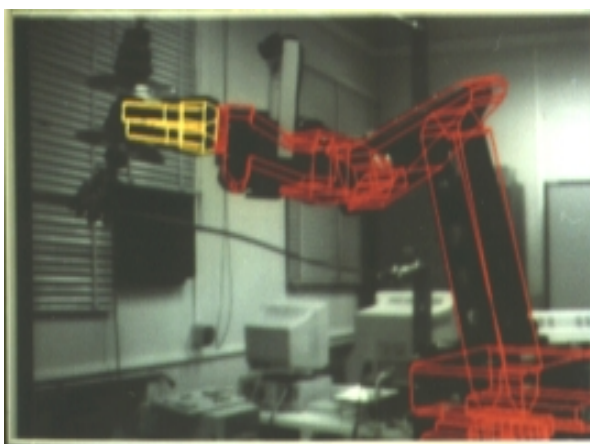


Figure 6. Images blending to check the computer model.

Through the calibration process, the operator must indicate the position of the elements of the environment. For the developed procedures, the calibration is carried out by using the manipulator. Before starting, the operator moves the manipulators at key positions referred to the remote site to calibrate the model. The key positions are the isolator chain ends, several points at the live lines and predefined points of the tower. To check the computer information, two images are blended. The first one is a video image from the remote working site and the second is a graphical simulation projected from the camera position, as shown in figure 6.

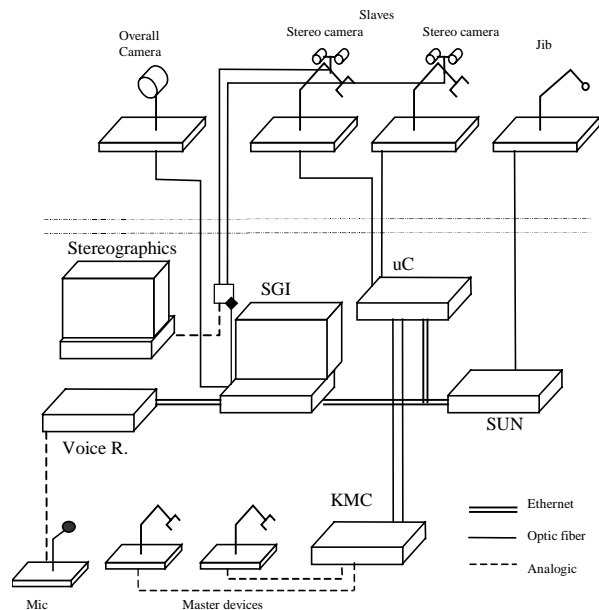


Figure 5. ROBTET architecture

4. ADVANCED TELEOPERATION TOOLS

A model with the element size, positions and the relation between them, provides several tools for the teleoperation system. In the ROBTET, the tools described below have been developed.

Voice recognition

This tool consists of a based word-by-word voice recognition system, called VISHA (Leandro 1993). It is necessary to be trained for each new operator and it has a 99% accuracy. VISHA receives the articulated operator words through a microphone, and they are translated to target language. This target language is a set of actions that the teleoperation system can perform. The operator controls the overall view, the procedure step, and the stereoscopic image selection by voice.

The operator interaction is similar to a menu. The operator says first the element to control, then the action to execute, and finally the command parameters if necessary. For example to move the overall camera, the operator must say "camera" + "pan" + "five", or "camera" + "overall_view". In the first case the operator controls the pan orientation directly, and in the second case the operator demands a predefined view.

Voice commands are useful because both operator arms are busy using the master devices. While the operator's hands are on the master arms, communication with the interface is done by voice.

The recognition rate is very important to obtain a proper operator interaction. A rate under 95% should make uncomfortable to use the voice system (Ferre 1998). The implemented interaction based on menus has the advantage to increase the recognition rate over 98% making it very friendly to the operator's interaction.

Collision detection

The collision detection algorithm employed is based on the successive approximation approach, in which the objects contour are successively refined as the algorithm progresses, as explained in (Bonner and Kelley, 1990), although we work with rectangular polyhedra (Aracil 1998). The detection algorithm is for static environments. In order to prevent the collision in the real environment, the objects in the model have been extended a safety buffer. In a typical environment of 32 solids + two 6 DOF robots, the detection algorithm lasts an average of 1.5 ms on the SUN machine. When a collision is detected, an artificial contact force is simulated and added to the measured forces on the remote environment before reflecting it on the master devices, as shown in figure 7. This prevents the operator from reaching the obstacle, avoiding the collision.

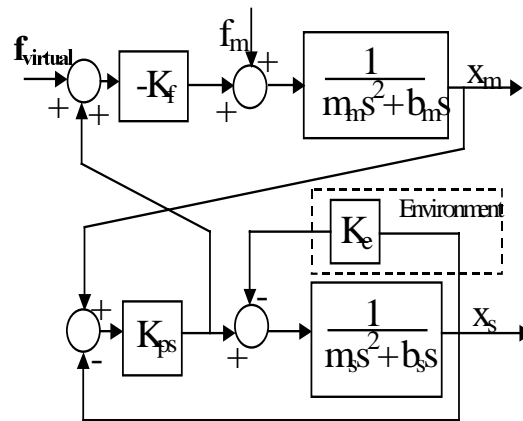


Figure 7. Master-slave arm control scheme

Real Time virtual force field based protection

Once a collision has been detected, it is necessary to compute the repelling virtual torques to be applied to the master device joints. First, the repelling force is calculated for the slave's tip or link. The force is a non-linear function of the depth of the contact and its direction is calculated following the basic guidelines given in (Kotoku, 1991), although, as explained in (Peñín, 1998b), some modifications were required to only work with static information during contact.

Through the use of the Jacobian matrix, equivalent joint torques are obtained, which are later passed to the force gain transform and control module on the KMC, just as if these torques had come directly from the torque sensors in the slave actuators.

The force is maintained as long as a collision is detected. Whenever the operator withdraws the slave from the forbidden zone this module becomes completely transparent. Figure 8 shows an example of the trajectory of the slave's tip following a virtual wall and floor contour using the developed system.

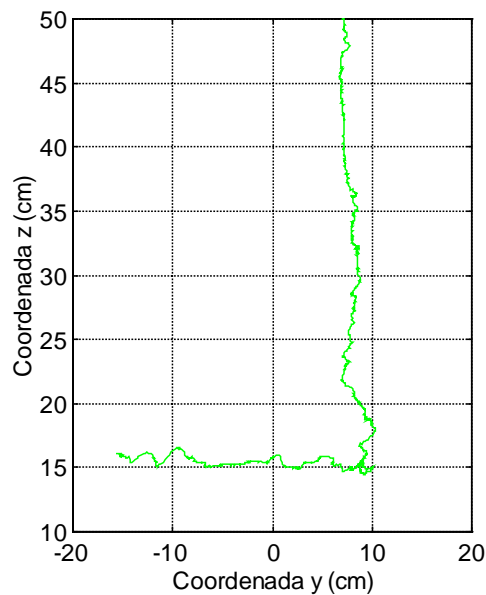


Figure 8. Path of the slave's tip during contact with a virtual wall and floor

Graphical simulation

A graphical simulation is the best way to show the three dimensional information to the operator on the computer (Ferre 1997). Graphics are used in the ROBTET for three purposes: to check the virtual model with the real environment, to show a view that it is impossible to capture from the used cameras and to highlight the solids and evolving virtual protections that incur in collision.

The check between the virtual model and the real environment is shown in figure 6. The virtual force generation and the collision detection are not activated if the mismatches between them are superior to the model tolerance. Tolerance depends of the short-circuit distance, that is related with the electric potential of the involved elements. Also the environment complexity is important to decide the tolerance. Working in a site with only the three live-lines is more safely than an environment including derivations, crossed lines or a transformer.

When the virtual model is calibrated, it is possible to display scenes simulated from the top of the manipulators. Sometimes this information is very useful for knowing the position of objects behind and forward manipulator grips. Neither stereoscopic cameras nor overall camera can show the environment from top or bottom views.

The elements are modeled as parallelepipeds. They are usually shown in a wired representation, but when a collision is detected, the corresponding parts are shown in a solid and highlighted representation. This change is very useful for the operator to know when a collision is detected.

Stereoscopic video cameras

The perception of depth is a very important factor to implement a precise manipulation. If the operator does not have a proper spatial information, he executes several movements before achieving the desired position, usually a zig-zag trajectory is

described, and therefore, task execution time increases and the teleoperated system performance decreases.

As previously mentioned, two stereoscopic video cameras have been mounted on the slaves. They are placed on the fifth link of each manipulator. Stereoscopic cameras have been developed specially for the ROBTET. They have two fixed color CCDs. The CCD convergence is calibrated according to the task, with a proper orientation in order to obtain a good perception with elements that are manipulated at distance of 50 cm.

The displayed stereoscopic camera is selected by the operator, and this image is processed by a Stereographics video system. It shows 100 images per second, 50 alternative images for each eye. The operator uses glasses to hide his eyes according to the displayed image. The stereoscopic images are very useful for the operator when he guides the manipulator to make a precise movement such as screwing.

5. TASK PERFORMANCE

Live-line works are done according strict procedures and rules. It is necessary to avoid faults and accidents. The manual procedures have been adapted to be carried out by the ROBTET. Modifications are related with the characteristics of manipulators and the possibility of using the jib. These rules must be considered to manipulate the live lines to avoid shortcuts.

Procedures

Several procedures have been defined for replacing isolator chains, opening and closing bridges and bypasses. These operations are common in this kind of work. Firstly, it is necessary to adapt the used tools in manual operation to be manipulated by the slaves. Secondly, it is recommended to simplify the tools in order to use only one or two of them. Many tools are inconvenient for teleoperated tasks, because the operations to pick up and return them to the box are slow.

Before starting the procedure execution, several operations must be done. First, connect the operator's cabin to ground and start up all the power supply. Then, place the tool in the platform box and position the platform in the remote working site. Finally, operator must calibrate the geometric model of the environment by using the manipulators. The procedure is defined by means of the sequence to carry out the task and the features of the elements for each step (e.g. electric potential). The operator indicates when a step is completed and then, the features of the model elements are updated. This information is used to check collision between elements at different potential.

Operator's training

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.

The final spent time is similar for many operators. To reduce this time, is necessary to use better tools, or introduce more automation in the procedure. Sometimes, new tools are easy to develop, but more automation involves new computers and sensors, that includes more complexity to the teleoperation system.

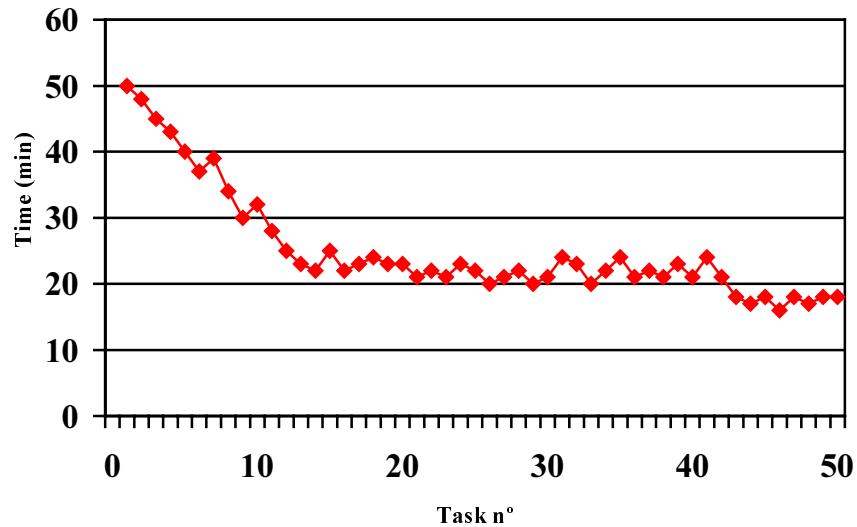


Figure 9. Operator training evolution

5. CONCLUSIONS

This paper presents the ROBTET project, a teleoperated system developed to fulfil all the requirements for live-line maintenance of the Spanish power distribution network (up to 46 kV). The system is fully operational and it is currently working satisfactorily.

New advanced technologies, applied in other fields, are being used and rationally integrated in this system, to greatly enhance the capabilities and performance of the basic teleoperation system. These technologies include solid modeling, voice processing, stereoscopic vision, and virtual force feedback. They are used to increase the operator's telepresence and its skills to execute the teleoperated task.

Other important results have been obtained about the operators' training, the procedures and the tools for this kind of jobs. It is very important to emphasize the necessity of getting a proper design of the tools for the way of working with the teleoperated system.

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References.

Aracil, R. et al (1995). ROBTET: A New Teleoperated System for Live-Line Maintenance, *6th IEEE Int. Conf. on Transmission and Distribution Construction, Operation and Live-Line Maintenance, ESMO-95*, Ohio, USA.

- Aracil, R., L.F. Peñín, M. Ferre and A. Barrientos (1996). ROBTET: Robot for live-line maintenance. *Int. Conf. on Live Maintenance (ICOLIM'96)*, Venice, Italy.
- Aracil, R. et al (1998). Obstacle avoidance for teleoperated robots for live power lines maintenance, using artificial vision. *IFAC's Workshop on Intelligent Components for Vehicles, (ICV'98)*, Seville, Spain.
- Bonner, S. and R.B. Kelley (1990). A Novel Representation for Planning 3-D Collision-Free Paths. *IEEE Trans. on Systems, Man and Cybernetics*, Vol. 20, 6, 1337-1351.
- Electric Power Research Institute (EPRI) (1987). Live-Line Repair with Tomcat, *EPRI Journal*, July/August.
- Ferre, M., R. Aracil, L.F. Peñín and A. Barrientos (1996). Multimedia Interfaces for Teleoperated Robots. *3rd SPIE Conf. on Telemanipulator and Telepresence Technologies*, Boston, USA.
- Ferre, M. (1997). Interfaz Diseño de interfaces para robots teleoperados. Desarrollo de un entorno de teleoperación con características multimedia (*in spanish*) *Ph.D. Thesis*. Universidad Politécnica de Madrid, Madrid.
- Ferre, M., J. Macías-Guarasa, R. Aracil and A. Barrientos (1998). Voice Command Generation for Teleoperated Robot Systems. *IEEE Ro-Man'98. IEEE Int. Workshop on Robot and Human Communication*.
- Kotoku, T. et al (1991). Environment Modeling for the Interactive Display (EMID) used in Telerobotics Systems. *IEEE/RJS IROS'91*, Osaka, Japan.
- Leandro M, and J.M. Pardo (1993). Low cost speaker dependent isolated word speech preselection system using static phoneme pattern recognition. *Eurospeech 1993*, vol. 1, pp. 117-120.
- Maruyama, Y. et al. (1993). A Hot-Line Manipulator Remotely Operated by the Operator on the Ground. *5th IEEE Int. Conf. on Transmission and Distribution Construction, Operation and Live-Line Maintenance ESMO-93*.
- Maruyama, Y. et al (1996). MV overhead hot-line work robot. *3rd Int. Conference on Line Maintenance, ICOLIM-96*, Venice, Italy.
- Peñín, L.F. et al (1997). Fundamentals of a master-slave teleoperation system with a force-position bilateral control scheme. *IFAC's Int. Symposium on Robot Control, SYROCO'97*, Nantes, France.
- Peñín, L.F. et al (1998a). Telerobotic system for live power lines maintenance: ROBTET. *IEEE Int. Conference on Robotics & Automation*, Leuven.
- Peñín, L.F. (1998b). Bilateral Control of Teleoperated Robots. Contributions on Force Reflection. *Ph.D. Thesis*. Universidad Politécnica de Madrid, Madrid.
- Santamaría, A. et al (1997). Teleoperated robots for live power lines maintenance, *14th Int. Conf. on Electricity Distribution*, Birmingham, UK.