Teleoperated system for live power lines maintenance

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ABSTRACT

Outage-free maintenance of electrical power lines have been developed and used throughout the years. In these techniques workers have to work near energized components with hazard of electric shock and falls. In this context, a teleoperator system is being developed to increase the safety of the workers and the overall efficiency. It counts with two hydraulic-driven master-slave teleoperated manipulators on top of an insulated boom over a truck. The operator commands the manipulators from a cabin on the truck via a pair of master arms, and it receives visual feedback through a stereo vision system.

Multimedia display, voice recognition and synthesis, stereo vision and force-feedback are some of the features being implemented in order to achieve telepresence of the operator. The paper addressed the implementation of these features on a teleoperation system prepared to work in a semi-structured hazardous environment performing repair and maintenance related tasks.

Keywords: teleoperation, telepresence, multimedia, supervisory control, stereo vision.

1. INTRODUCTION

As a consequence of today's highly information oriented society and increasing demand of electricity, uninterrupted power supply has become indispensable for utilities. Outage-free maintenance techniques in overhead distribution lines have been developed and used in Spain for more than 25 years in order to achieve this. In these conventional techniques workers have to do their job on a live electrical power line, indirectly with various kinds of hot-sticks or directly touching the line with rubber-insulated gloves. Therefore, work is performed in a hazardous environment with both the risk of electric shock and the danger of falling from a high place. In addition, workers have to be very skilled and work cooperatively under very demanding tasks.

To both increase the safety of the workers and the overall efficiency of the maintenance tasks, a teleoperator system called ROBTET is being developed. Two hydraulic driven manipulators, placed on a rotating platform on top of an insulated boom substitute the workers in performing the hazardous work on the hot line. The operator, instead, is located on the ground from where he teleoperates the slave manipulators via two force-reflecting master arms. Therefore, in order to do the work properly, is indispensable that the operator feels as close as possible as if he is performing the job directly, and even in some aspects augment his capabilities. So, some kind of mechanism is needed to achieve this telepresence. In our particular application telepresence is accomplished through several means. First, a stereo vision system is used to maintain an updated model of the environment, simulated over the image of an overall-view camera. In second place, these images and the simulation, with additional information regarding the task being done, are presented in a multimedia interface with voice synthesis and recognition. In third place, the two master arms are equipped with force-reflection capabilities, and finally path planning and collision checking algorithms improve the performance and safety of the system.

This paper describes the system as a whole, making special emphasis in the architecture implemented and the solutions adopted regarding telepresence, having always in mind the application for what is directed.

2. OVERVIEW OF TELEROBOTIC LIVE-LINE MAINTENANCE SYSTEMS

Live electrical power lines maintenance encompass a series of operations (insulator string replacement, derivations, opening/closing bridges, etc.) made of highly standardized manipulations procedures, some of which are common to different operations. Having also in mind the hazardous environment in which these operations take place, it is clear that some kind of teleoperated system can be introduced with great advantages. Utilities around the world have also been aware of the capabilities of teleoperation for this application. Since the first telerobotic developments back in the mid-eighties by two companies[1-2], several systems have been presented through the years[3-7], while other utilities also have shown some kind of interest on the subject[8].

The main advantages introduced by these systems are: (1) the ability to do and improve outage-free maintenance in countries with strict regulations regarding human interaction with hot lines, (2) the increase in safety of the workers, (3) the decrease of cost by eliminating the need for the operator to be working in a hazardous environment (wages, insurance, special equipment, etc.), (4) ability to work under moderate bad weather conditions and (5) decrease of labor requirements. A disadvantage is the increase in execution time, which is greater than manual operation[9] in the actual state of the telerobotics systems. However, it will become shorter than manual operation with the new technological improvements, as shown in this communication.

Each of the systems developed has been specially designed to fulfill the requirements of their specific application. All have in common the need of a truck with a boom to reach the lines, and the use of some kind of manipulator on its top, but in relation to the mode of operation, which defines its practical and efficient use, they differ. Table 1 shows a comparison regarding various aspects of several modes of operation of this kind of systems

Table 1

Comparison between various mode of operation for live-line work

Mode of operation	Human safety	Cost	Reliable	Work force	Workers qualif.	Weight	Control complex.	Sensor complex.	Protection	Producti-vity
Manual	↓↓	↑↑	↑↑	↓↓	↓↓	↑	↑↑	↑↑	↓↓	↑
Manual Direct Tel.	↑	↑	↑	↑	↓	↓↓	↑	↑	↓	↑
Manual Ground Tel.	↑↑	↑	↑	↑	↓	↑	↑	↓	↑↑	↓
Semiautomatic Direct Tel.	↑	↓	↑	↑	↓	↓↓	↓	↓	↓	↑
Semiautomatic Ground Tel.	↑↑	↓	↑	↑	↓	↑	↓	↓↓	↑↑	↓
Automatic	↑↑	↓↓	↑	↑↑	↑	↓	↓↓	↓↓	↑↑	↑

Note: The ↑ and ↓ symbols indicate a factor more or less favorable

Our system can be classified as semiautomatic with the operator on the ground. In a first stage supervisory control in some degree is expected, while the final objective is to reach supervisory control next to fully automatic control. Its mayor components are shown on figure 1 and are briefly described on table 2. It is necessary to add that it has been designed to do maintenance tasks in lines of distribution networks of up to 49 kV.

Table 2

Equipment Specification

Truck	5.5 ton, 8 m long
Boom	15 m long, telescopic and with up to 69 kV of dielectric strength
Cabin	Mounted on truck chassis, next to truck cabin. Includes the operator post with the boom, jib and manipulator control stations
Visual sensors	Stereo vision system (3-axes + zoom). Overall-view camera (2-axes + zoom)
Manipulators	Hydraulic, 7-function (6 axes + grip), articulated. masters with force-feedback, max. payload 45 kg/arm, net weight 60 kg/arm
Jib	Hydraulic, 3 dof, telescopic, lifting capacity: 200 kg; with winch
Rotating platform	Mounted on top of the boom. Holds the slave manipulators, the jib and the visual sensors.

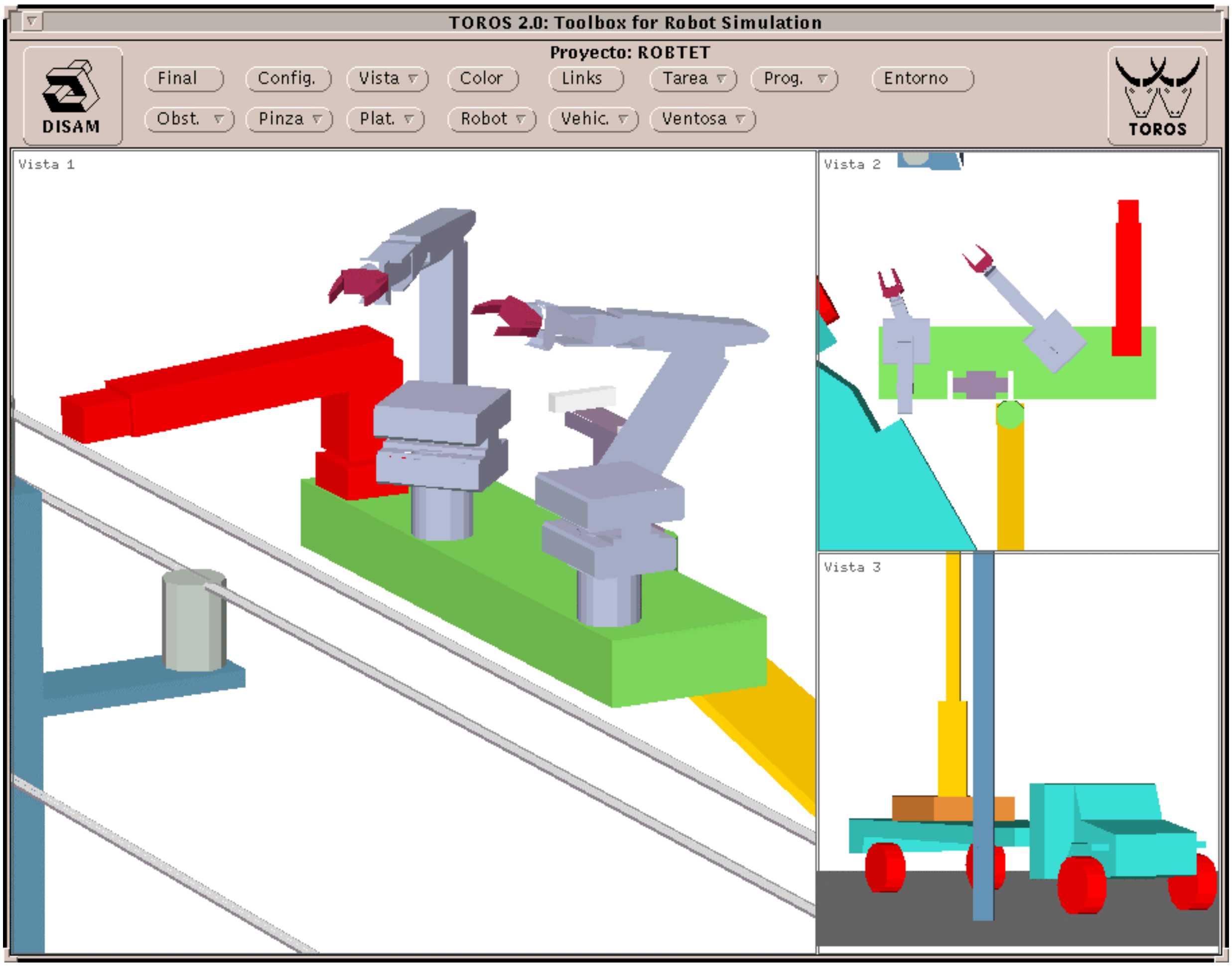

Figure 1. ROBTET main equipment

3. FUNCTIONAL STRUCTURE

The main objectives of the teleoperated system structure is to give the operator as much feeling of telepresence as possible, and to able to perform remote tasks correctly and in short time. Three modules are implemented to accomplish this. The first one, located in the operator's control post, is called *human interactive computer* (HIC)[10], an its mission is to interact with the operator in order to close the control loop. The second one, named *task interactive computer* (TIC), receives commands from the HIC, processes them, and interacts with the equipment in the remote zone in order for them do the task. The third module has as its main job to process the remote sensors information, and is named *sensor processing computer* (SPC). Figure 2 shows a functional scheme with the different elements and their relation. Next sections will explain them in detail. The communication between modules is made by ethernet, whereas into the TIC and the SPC is by VME bus. This allows to send commands easily between modules, and at the same time have a high information exchanged speed within each one. The HIC has a proprietary bus with high bandwidth to display video in real-time.

The teleoperation architecture developed is based on the NASREM[11], implementing only the first four levels. In our case, special attention has been put on the development of the operator interface, based on an advanced multimedia display. The interface consists of the HIC with the appropriate devices in order to give commands and receive information. It has the following main features: voice synthesis and speech recognition; video and simulation blending, and masters with force-reflection capabilities.

The system allows two control modes: (1) manual, with the master arms and (2) supervisory control, sending high level actions to the manipulators. Therefore, two different kinds of commands exist. On one hand, low level orders that are direct positions to the manipulators, and on the other hand, high level commands to do predetermined tasks. Low level orders do not need much processing (joint transform and control, collision checking, etc.), while high level ones need to generate low level actions on several devices, and therefore need to process more and to access data from the environment data base.

As explained above, a model with the working remote environment is indispensable. This model with a geometric and functional description is stored in a global data base. An extrusion model has been chosen for its simplicity and good performance. The following functional classes of objects have been defined: (1) passives: those elements without independent movements and (2) actives: those elements with independent movements; while the relations between them can be: (1) fixed: with bi-directional relations; (2) supported: with unidirectional relations and (3) manipulated: with no fixed or supported relation.

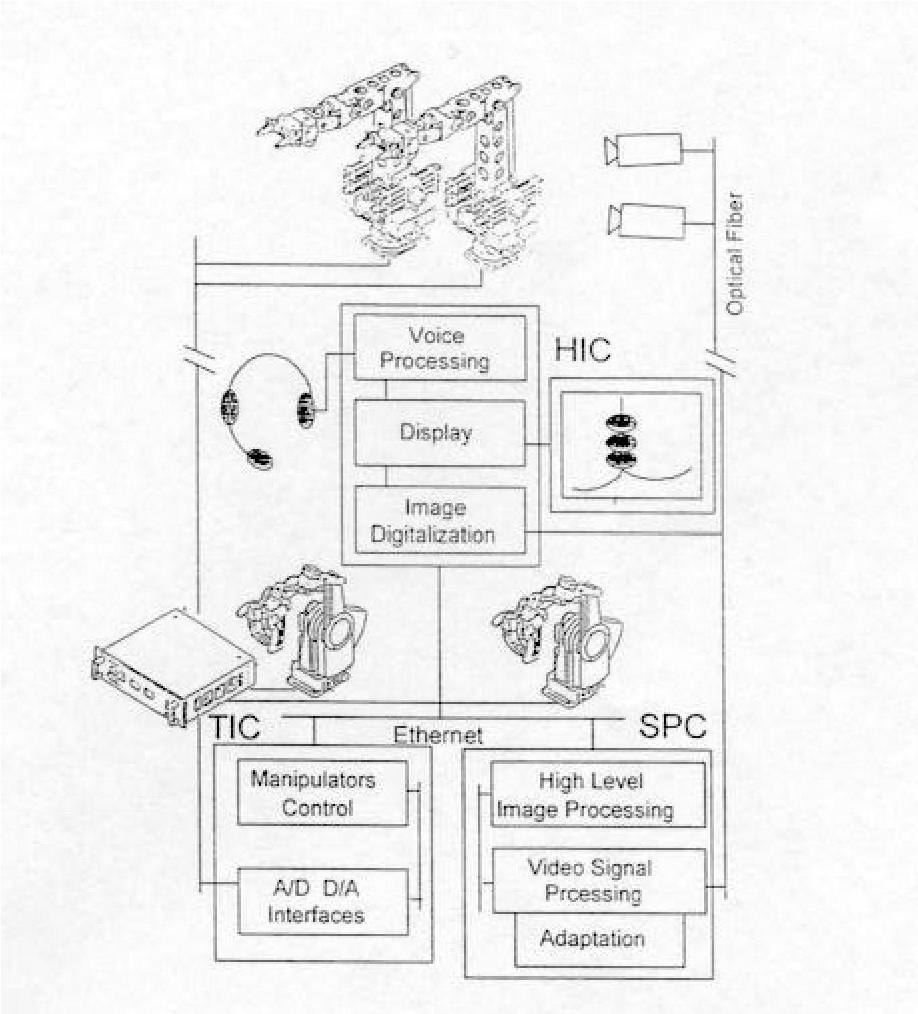

Figure 2 System structure

The global data base is in the TIC, and the HIC and SPC read and write information by ethernet. Each module accesses the data base through an special interface, so there is only one environment information, in order to have congruent model, but every module has its own remote environment representation. It is necessary to have different representations because the HIC, TIC and SPC process the information in a different way. For example, the TIC updates the manipulators positions and the SPC updates de positions of the rest of the elements, but the TIC works with articular positions while the SPC uses 3D contours.

4. HUMAN INTERACTIVE COMPUTER (HIC)

The HIC objective is twofold: (1) to manage the inputs from the operator in order to send them to the TIC and (2) to show the operator the necessary information in order to perform teleoperation, providing the operator with the maximum degree of telepresence. To be able to perform an adequate control (manual and with supervision) depends in a great measure of the HIC development, and in a lesser part on the low-level control of the manipulators, very similar to the one present in conventional robots.

The different I/O devices processed by the HIC are: a) *Inputs* from the operator to the HIC: master-arms and manual controls, voice and push-buttons. b) *Outputs* from the HIC to the operator: video, simulation, voice synthesis, force feedback and other data from the remote zone.

4.1 Inputs from the operator to the HIC

The master arms are the only devices which are able to generate inputs on level two of the NASREM (trajectory generation). The master arms used are two anthropomorphic right and left arms, with manipulators equivalent kinematic. They allow to work in manual control. That lets the operator to get tools and to manipulate elements by himself. The processing by the HIC is minimum, only some joint scaling and transformation, inertia compensation and counter-balancing; however other inputs, like joysticks, need more processing.

Voice commands correspond to inputs to the third level of the NASREM (elementary moves), and need a high level processing in order to obtain control commands for the slave arms. Speech orders are translated into a primitive set called *target language*. The target language is the minimum actions that can be made by the teleoperated system; these actions are related with the manipulators and jib movements, the vision control system, and the teleoperated system configuration. So the operator command can be *get the stick*, and this is translated into a sequence movements to the robots. This movements commands belong to the target language set of commands, while the positions are stored in the data base. Examples of other high level commands are *increase azimuth 20, blend simulation with camera 2*. Figure 3 describes the process of action recognition from voice command. In first place the sound signal is processed, and a subsequent syntactic and semantic analysis of the statement is performed. With both analyses a statement that makes sense to the computer is obtained, allowing to understand the command said by the operator. Next, an integration of the speech has to be done in order to obtain the parameters for the *target language*. This parameters usually refer to positions and therefore the environment data base has to be accessed. The last level of processing is an analysis of the commands coherency. These voice commands involve the major part of the communication between the HIC and the operator, and refer both to manipulators actions and to management, configuration and working of the HIC.

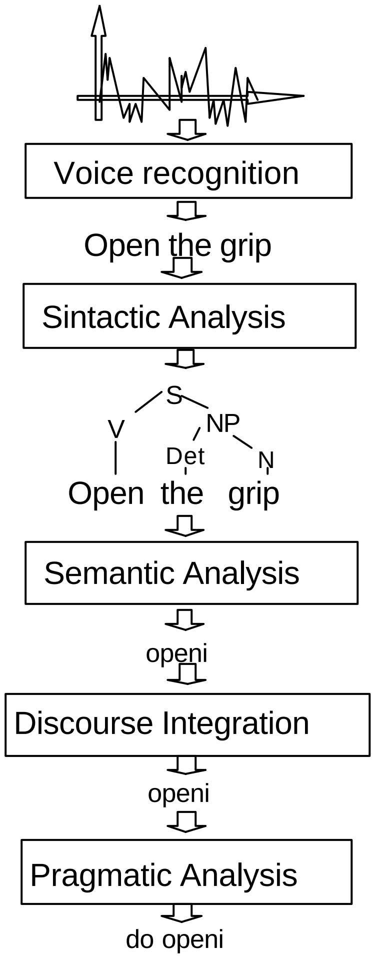

Figure 3: Recognition procedure.

The operator may also count with several manual controls for other equipment like cameras, jib and boom. The stereo vision manual control devices needs to have 3 dof, and 2 dof for each camera. It is, therefore complex to do the manual control with joysticks, so the HIC allows the operator to position some of the dof by voice and others manually. There are also other manual devices to position the jib and the boom. The rest of inputs are done by means of push-buttons with two main objectives: (1) reply to confirmation requests from the HIC and (2) to respond in case of emergency and critical situations.

4.2. Outputs from the HIC to the operator

In a display the HIC shows two video images from the remote site and a simulation from the current task. In the remote site there are four cameras but experiments show that the operator fixes his attention in only one image. The second image support the teleoperation in order to show the depth on the first image. So is important that the two simultaneous images showed are not aligned. The simulation has two objectives, the first one is to check the environment with the model into the data base, and the second is to show the simulated scene from different points of view, which has proved very useful to achieve teleproprioception of the operator. The check is useful when the task is starting, because the HIC shows to the operator a blended image with a view from a camera and the simulation from the same point of view of that camera[12]. When the task is running, the simulation may show hidden views from the working remote site. The operator can change the cameras in the middle of the task to show different views. Figure 4 shows an example of the blending process: three different images show respectively the simulation of an arm, the video image of the arm an the mixture of both.

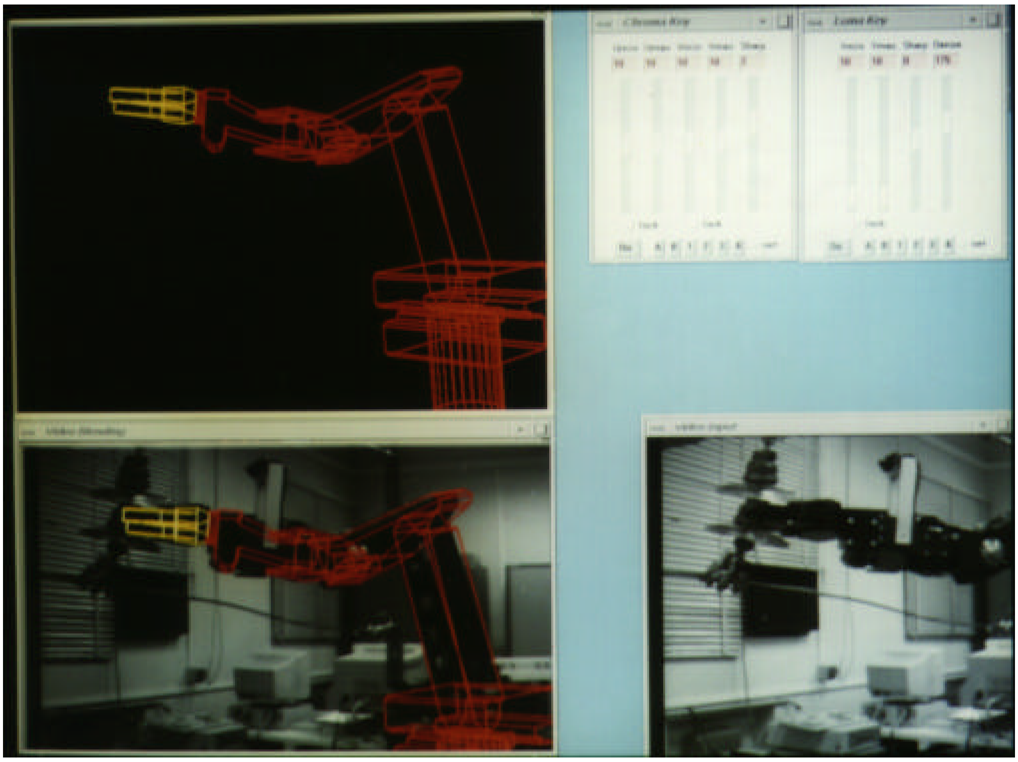

Figure 4 Blending of simulation and video

Another important output to be considered in the teleoperation performance is force-feedback of the force exerted by the manipulator on the environment during manual control. This force is reflected on a master arm with position control. As shown by Das et al.[13], this kind of manual control mode is one of the more preferred by operators and ranks among the best in overall performance of completion time and average and cumulative force exerted.

The HIC informs to the operator about the task performance through several means. One is voice messages synthesis and another is by the representation with graphics of the evolution of some important variables i.e. forces and torque exerted by the manipulators.

5. TASK INTERACTIVE COMPUTER

The Task Interactive Computer (TIC) is the machine that receives commands from the HIC, and do the proper actions on the manipulators and other controlled devices in the task environment. Usually located at the remote location to cope with time delay, in our particular application is in the operator post for insulation reasons and connects to the remote location, at a maximum distance of 15 m, through fiber optic.

In case of manual control, it also processes the master-arm controller commands as well as signal from other manual controlled devices, such as cameras. The force and joint position of the slave arms are feedbacked to the HIC as real-time information of how the manipulators are proceeding with the task. Figure 5 shows an schematic view of the TIC in an overview of the whole system. This scheme, based on the ones by Das[13], has been simplified and it only includes major components (one master-slave system) and main information flux channels, because, as has been explained in the preceding section, much of the information not used in real-time processing is exchanged between blocks through a global data base. For example, the manipulator positions between the position sensors and the HIC. The main units of the TIC are:

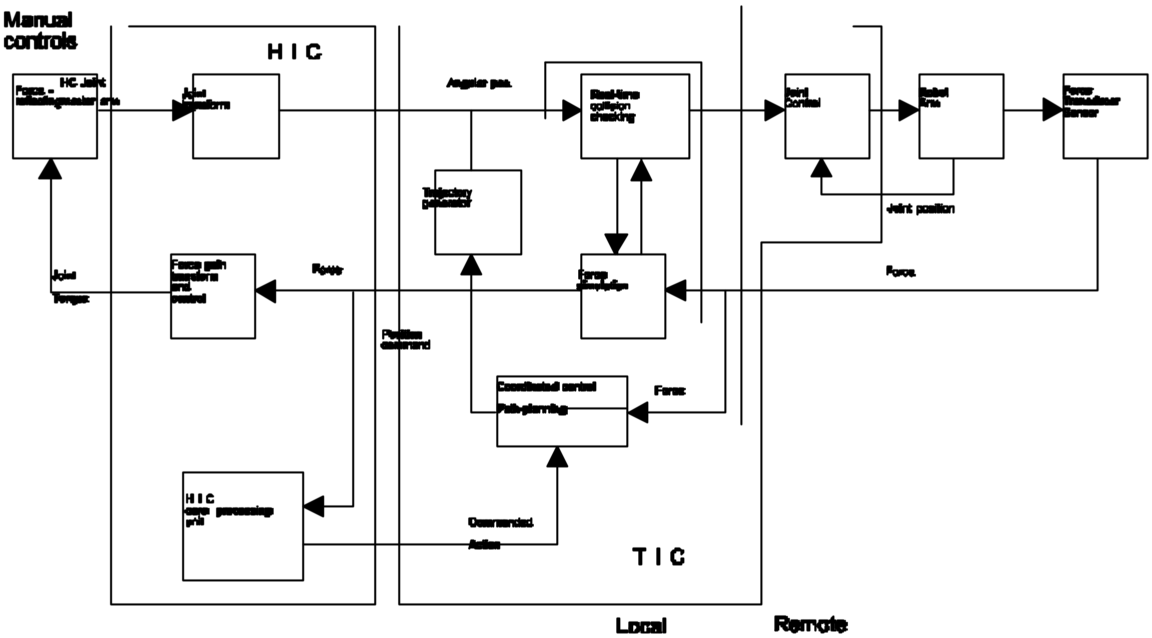

Figure 5. TIC block scheme

5.1 Joint control

This module corresponds to the first level of the NASREM. Is what it can be called the servo level of the equipment working in the remote zone. In our configuration, although the TIC is mainly on the local zone, this unit is situated on the remote zone, next to the controlled equipment. It receives reference positions for each joint which are compared with observed positions, generating electrical signals to the electrovalves driving the actuators of both the jib and the manipulators, and electrical currents to drive the actuators of the vision system.

5.2 Trajectory generation

This module corresponds to the second level of the NASREM architecture. Its objective is to generate smooth, dynamically efficient trajectories between commanded positions in consecutive time intervals. The commanded positions (position, orientation and configuration) come from the path-planning module of the TIC during supervisory control. It generates evenly spaced trajectory points which define a dynamically efficient movement. They are transferred in joint coordinates to the next block.

5.3 Path planning and coordinated control

This module corresponds in some way to the third level of the NASREM. It only has some meaning in the time intervals in which supervisory control is assumed. From the symbolic commands in the target language generated by the HIC, this module generates strings of intermediate positions which are free of collision and kinematic singularities in order to fulfill those commands. The path-planning is used to do some routine operations, such approaching the work zone, grasping a wire, screwing, etc. relieving the operator from some of his work. In a more advanced stage it would be useful to perform automatic operation. The path-planning method chosen is the local C-space[14], with some variations[15] based on simplifications proper of the environment we are working with. It is performed based in an environment model generated and continually updated by the SPC.

In this same module coordinated control of both arms is included. In coordinated control, two main aspects have to be considered[16]: (1) the pure planning of coordinated actions between manipulators, that can be take into account part of the path planning and (2) the consideration of compliance in the interaction of both arms. Position information can be obtained directly from the environment, while force comes directly from the pressure sensors on the manipulator actuators. It has been seen that for most of the tasks the cooperation is reduced to have one arm holding some element while the other works on it. The algorithms, therefore, are simplified.

5.4 Real time collision checking and force simulation

This fourth module of the TIC does not fits exactly with any level of the NASREM architecture. Its mode of operation is twofold. In first place performs a real-time checking of collision between the objects in the environment during the manipulators movement. It gets the information of the environment from the updated model in the SPC, the current position of the manipulators directly from the joint position transducers and of the arms next desired position from the joint references of the master arm or the trajectory generator. This checking is considered as a safety measure needed to prevent unintentional collisions. This is extremely useful to avoid provoking a shortcut between phases of the three wire live lines. One wire is the working one while the other two are considered obstacles with the tower. It can be applied not only to a manipulator arm but to any object that is being moved manually in the environment. The checking algorithm being develop is based in the one by Shaffer[17]. The main idea is to use N-octrees to model the environment.
On the other hand, when an imminent and unintentional collision with an object defined as an obstacle (not performing operations on it) by the operator will take place, the new reference of position is not sent to the joint control module and an artificial force is simulated on the master-arms, substituting the original one. This prevents the operator from reaching the obstacle and therefore the collision is avoided. This force is also sent to the HIC as crucial information for the operator, and the environment can be modeled as a force field with maximums in the locations of obstacles, similar to potentials fields for path-planning .

If no collision is imminent, this module is absolutely transparent for the data going from the trajectory generator to the joint control, and for the information of force coming from the force sensors. This module is considered essential for safety reasons both in direct and supervisory control.

6. SENSOR PROCESSING COMPUTER (SPC)

The Sensor Processing Computer (SPC) update the database with the model of the environment, needed for the HIC and TIC. The SPC is made by a vision system, which is made up of an acquisition subsystem integrated by a stereo mount with tilt and vergeance control for each camera equipped with zoom and focus control. There is also a laser illumination system to improve the segmentation of cables. This sensor feeds and image processing set of VME boards with pipeline architecture that implements the preprocessing, segmentation and feature extraction process. These selected features are a representation of the edge contours of the scene carried out by a linear segment approximation. The vision control CPU feeds the feature information by an ethernet link to a multiprocessor system that holds the database of the environment, the vision process, and the path planning and collision algorithms. The data base is update by a stereo algorithm that recovers the three-dimensional information of the tower contours and match this information with a model data base in order to generate en accurate location of the tower and his elements such as insulators, fittings and cables.

The laser illumination system solves the equipolar collinear ambiguity of the stereo system. This allows an easier recovery of the exact parametric model with the location of the cables. For the tower location, a polyhedral model was chosen. At the heart of the 3D reconstruction is a feature oriented stereo algorithm based on a set of local, and global geometric constrains that solve the correspondence problem between primitives of both images. From the resulting matches and the calibration information, a 3D contour model of the tower is generated, that is treated as an obstacle. For some types of standard tower an additional recognition stage is introduce to improve his location accuracy and allow automatic maintenance tasks. The last element to introduce in the base is the insulator. Typical insulators used in electrical towers have a curved shape. In order to find his location it is handled by means a polygonal approximation of the external box contour. This approach allows to generate an excluding area for the robots. The maintenance of internal elements es carried out from the information of the model database for known types, and teleoperated for non standard isolators.

7. CONCLUSIONS

This paper has presented a new teleoperated system for live-line maintenance called ROBTET, being designed to fulfill all the requirements for live-line maintenance of the Spanish power distribution (46 kV) network.

New advanced technologies, traditionally only applied in other technical fields, are being used and rationally integrated to greatly enhance the capabilities and performance of the basic teleoperation system. These technologies include 3D environment modeling, voice processing, path planning, collision avoidance, multimedia interface, telepresence, learning, etc., making the ROBTET a system being designed with the latest developments, having in mind what is going to be the future of everyday operation in hazardous environments

8. ACKNOWLEDGMENTS

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9. REFERENCES

1. EPRI. “Live-Line Repair with Tomcat”. EPRI Journal, July/August 1987.
2. Maruyama, Y. et al. (Kyushu Electric Power Co.), “A Hot-Line Manipulator Remotely Operated by the Operator on the Ground”. *5th IEEE International Conference on Transmission and Distribution Construction, Operation and Live-Line Maintenance ESMO-93*, 1993.
3. Bennet, T. (Pacific Gas & Electric Co.) “Creating Solutions. Utility company puts robotic arms to work”. Lift Equipment, August-September issue, 1993
4. AICHI Development Planning Department (1990). “Aichi Manipulator system Design Feature”
5. Ueno, T. (Shikoku Electric Power Co.) “Development of Hot-Line Maintenance Robot”, *Workshop on Robotized Hot-Line Maintenance*, Pisa University, Italy, 1988.
6. Boyer, M et al. (Hydro-Quebec Power Co.) “Telerobotics for Maintenance of Distribution Lines”, *International Conference on Line Maintenance*, *ICOLiM-94*, 1994
7. Yokoyama et al. (Tokyo Electric Power Co.) “Manipulator System for Constructing Overhead Distribution Lines”, *5th IEEE International Conference on Transmission and Distribution Construction, Operation and Live-Line Maintenance ESMO-93*, 1993
8. Soler, R and Guillet, J, “Robotic Maintenance of the EDF transmission (63 to 400 kV) network: feasibility Study and effects on tower design”. *5th IEEE International Conference on Transmission and Distribution Construction, Operation and Live-Line Maintenance ESMO-93*, 1993
9. Lessard, J.L. et al., “Evaluation of working techniques using teleoperation for power line maintenance”, *SPIE Proceedings on Telemanipulator and Telepresence Technologies Conference*, Boston, 1995.
10. Sheridan, T.B., *Telerobotics, Automation and Human Supervisory Control*. MIT Press, Massachusetts, 1992
11. Albus, J. S., McCain H.G. and Lumia, R., “NASA/NBS Standard Reference Model for Telerobot Control Sytem Architecture (NASREM)”, *NIST Technical Note 1235*, 1989

12. Balaguer, C., Aracil, R. et al , "TOROS: Graphical toolbox for Robot Simulation". *International Workshop on Graphics and Robotics*. Schloβ Dagstuhl, Germany,1993
13. Das, H. et al "Operator Performance with Alternative Manual Control Modes in Teleoperation", *Presence*, Vol 1, Nº 2, pp. 201-217, 1992
14. Lozano Pérez, T, "Spatial Planning: A Configuration Space Approach", *IEEE Transactions on Computer*, Vol. 32, Nº 2 , 1983
15. Rodriguez, F. J., *Free Collision Path Planning for Robots in 3DEnviroments*, Ph. D. Thesis. Polytechnical University of Madrid, (in Spanish), 1993
16. Rodriguez, C. F. *Control and Planification of Multirobot Systems Working in Coordinated Taks*, Ph.D. Thesis. Polytechnical University of Madrid,(in Spanish), 1994
17. Shaffer, C. A. and Herb, G. M., "A Real-Time Robot Arm Collision Avoidance System", *IEEE Transaction on Robotics and Automation*, Vol 8, No. 2, pp. 149-160, 1992
18. Aracil, R. et al. "3D Dynamic non Structured Environment Modelling by means Artificial Vision, for Robot Trajectory Planning", CICYT Technical Report, 1995.