SRT Project: Telerobotics maintenance of Nuclear Power Plants

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ABSTRACT

The main aim of the SRT project was to develop a family of robots to help in the operation of nuclear power plants. Four robotic systems were developed and this paper focuses on three of them: ANAES –a steam leak detector through noise analysis–, MALIBA –a master-slave teleoperation system with force feedback– and ROBICEN –a compact pneumatic wall climbing robot–.

ANAES (the Spanish acronym of spectrum analysis) consists of a set of sensor heads attached to a computer. Each head has two microphones and a video camera installed on it, and a DC motor that rotates the head. The heads are shielded with lead and boron steel, especially near the video camera. The noise generated by the plant is recorded every day at the same time and the software compares the recorded noise with the mean values of past records. The system can discern whether the noise has remarkably changed and, through phase analysis of the sound recorded by both microphones, identifies the direction of arrival (DOA) of the new noise, probably a steam leak. Using several heads, the new noise source can be identified. The video camera can be used to ease the location of the steam leaks. The stationarity of the measured noise has been tested in C.N. Cofrentes –a Spanish BWR-6 reactor–. A finished system with six heads has recently been installed in the MSR (moisture separator reheater) of the same plant.

MALIBA is a master-slave teleoperated system with force feedback. It consists of two robots: a Stewart platform used as master robot and an open chain robot used as slave. The slave robot follows faithfully the movements of the master, and the master robot can reflect a force proportional to the force exerted by the slave on the environment. Three tools have been developed for the slave robot: a robot hand that includes a small video camera, a pneumatic drill and a rectifier. The results obtained have shown its effectiveness for the designed operations.

ROBICEN is a lightweight pneumatic robot weighting 3 kg designed for the inspection of rad waste cylindrical tanks. The design is very compact (its length is 215 mm). With a novel locomotive mechanism based on pneumatic actuators and suction pads, it is able to climb vertical walls at speeds close to 110 mm/s. Since its adherence is based on vacuum generation, it can climb non ferric surfaces unlike other robots based on magnetic adherence. The robot has several video cameras installed and an ultrasound sensor to measure the thickness of the tanks.

ANAES

Introduction

ANAES is a small hardware device whose need was established by nuclear power plants wishing to reduce radiation absorption in maintenance staff during detection and repair of steam leaks. Its main function is the detection and location of steam leaks in pipes and valves. The acoustic waves generated by leaking steam are first detected by two small microphones, then captured by a sound card and finally converted to the frequency domain by spectral analysis. By comparing short and long-term averages of power spectra with the actual spectrum, the presence of steam leaks can be detected and located. A small CCD video camera conveniently shielded against radiation is used to make visual inspections and to show the areas where steam leaks have occurred.

ANAES has been developed jointly by CEIT and ENSA within the SRT project, with financial support of Iberdrola and Endesa.

Mechanical design

Three initial prototypes were developed before achieving the final system. In the first prototype, the head had a video camera, two microphones and an ultrasound microphone. This prototype can be seen in the left photograph of the Figure 1. To ease the mechanical design no position sensor was installed. The first tests with this prototype showed the need of a position sensor since estimating the position of the head in function of time was not accurate enough. A second prototype with a potentiometer to measure the position was developed. The rest of the mechanical design was only minimally changed.

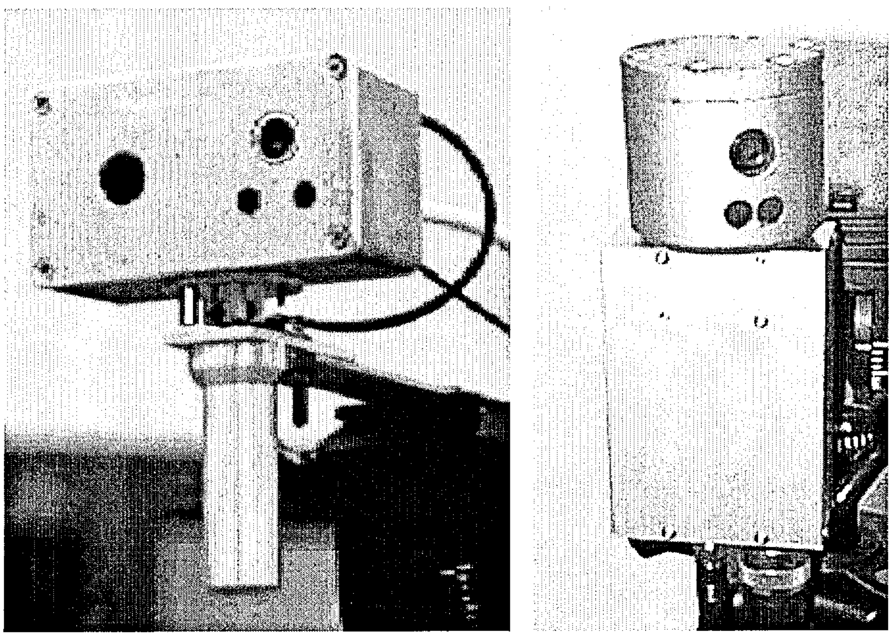

Figure 1. Initial and Final prototype of ANAES heads

The right photo in Figure 1 shows the definitive system prototype. This system is much more compact than the previous designs and is shielded against radiation with lead and boron steel. The ultrasound microphone was suppressed because the information obtained from it was not relevant. Each ANAES head is connected to a teleoperator console that can manage up to ten of them.

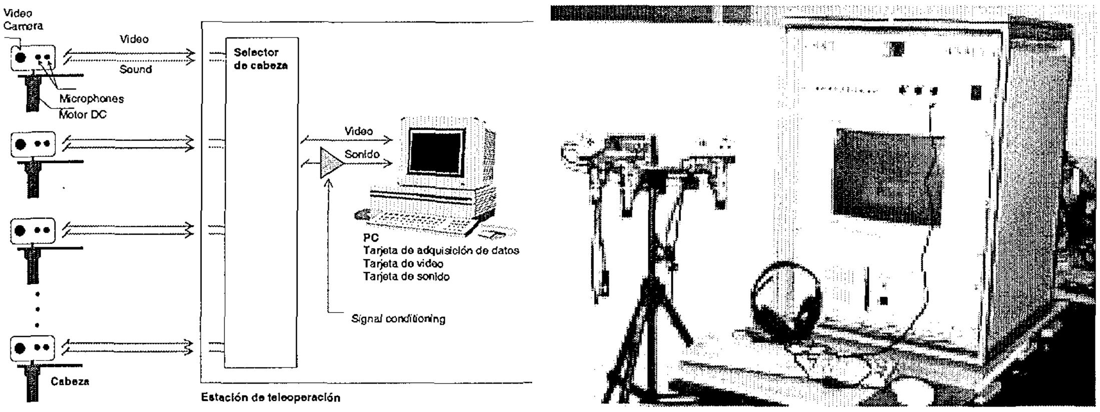

Figure 2. Scheme of connection of the ANANES heads. Photo of the system.

Software

The software of ANAES can be divided in four main parts: the scheduler, which is in charge of recording the noise on each unit of ANAES, the leak detector, which discerns whether a leak exists, the leak locator that finds the direction in which the leak has been produced and the camera control.

Scheduler. The scheduler is usually set to record on a daily basis in the period 2:00 am - 3:00 am, which improves the chances of getting a lower dispersion in the records. Data registered with each unit is automatically stored in the hard disk and processed to obtain frequency spectra. Since the leak detection is based on the stationarity of the sound, this is a crucial characteristic of the analyzed sound. The power spectra of the recorded sound during 40 days in C.N. Cofrentes can be seen in Figure 3. The peaks that appear in 7.8, 8.2 and 15.5 kHz are related to the acquisition circuit. They do not appear in the sound of the plant. Every day at a fixed hour (2:00 am) the system starts to record the sound for each head (up to ten) and for each position of the head (33 positions equivalent to 10º). The whole record takes 1 hour. This mobility of the head makes this system much more robust because of the increment of the number of data to analyze.

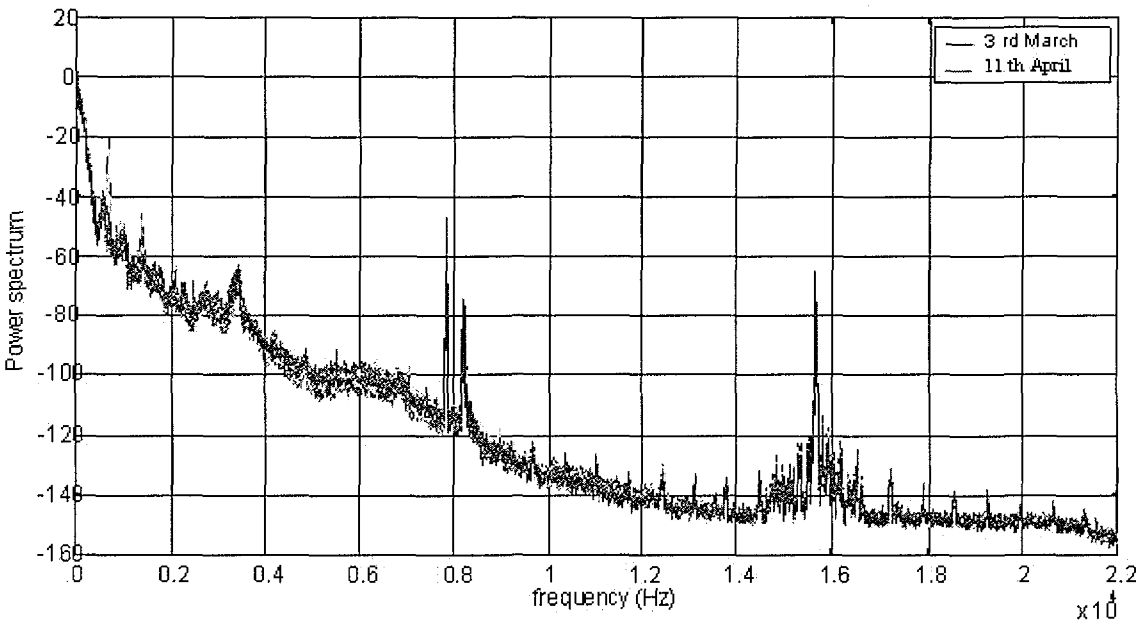

Figure 3. Spectra of the recorded sound during 40 days

Leak detector. It browses through data registered in the last weeks. By comparing the frequency spectrum of the most recent day with averages of previous days or weeks, the program automatically calculates and displays the frequency band where discrepancies with averaged spectra are outside the interval of confidence. This interval depends on the variance of the magnitude of the sound for each frequency. The main window of this part of the program can be seen in Figure 4.

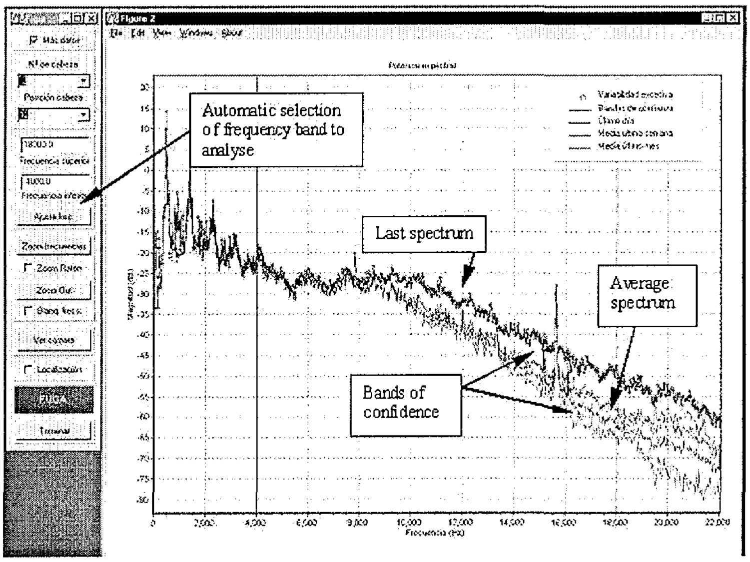

Figure 4. Leak detection window

Leak locator. Once determined the frequency band, in which a steam leak has occurred, this module computes the phase lag between the two microphones for every frequency and for every position of the heads. By plotting this data, a larger density of points can be noticed in the direction of the leak. Figure 5 displays a window that shows an artificial generated leak.

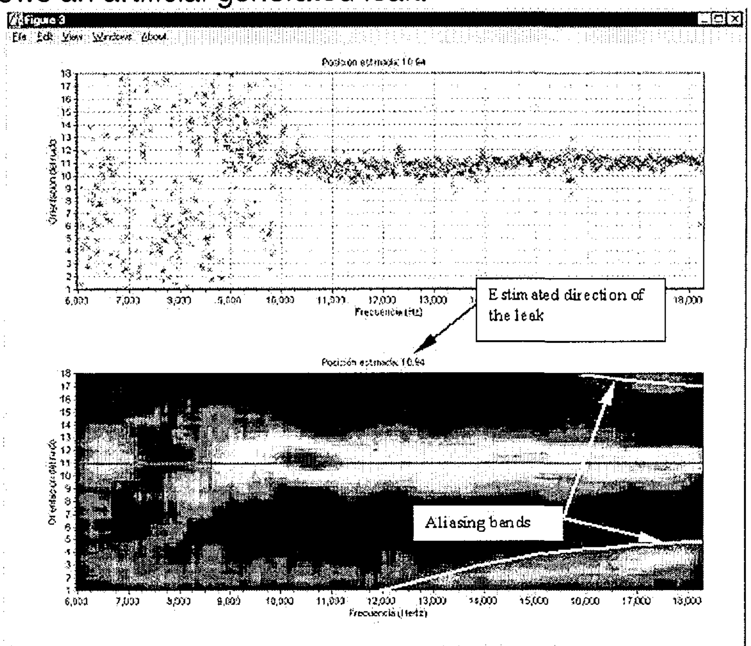

Figure 5. Location window. This window displays a system with a leak in the direction 11.

Camera control that is used to point the camera in the desired direction and to set up properties available for video and image capture. Figure 6 shows a image taken from the camera and the control of its direction.

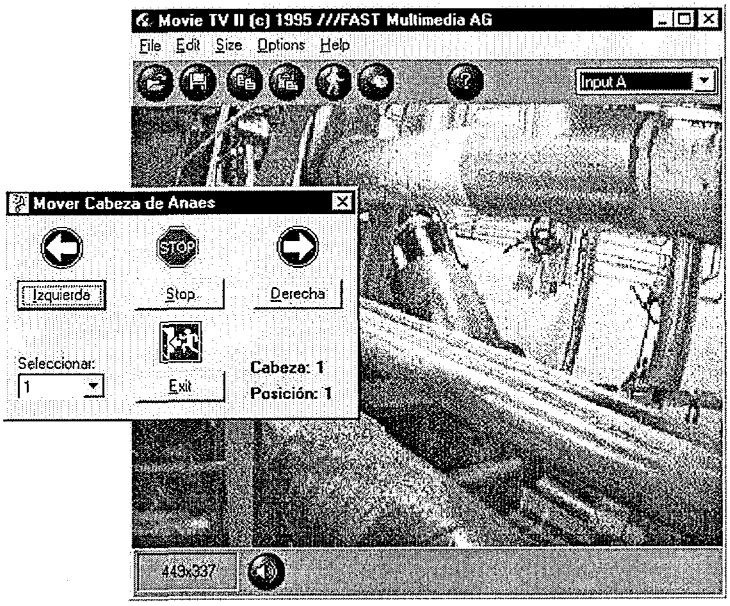

Figure 6. Image taken from the camera.

To validate the developed algorithms, tests have been made in the laboratories of CEIT and ENSA simulating leaks in a noisy environment. The tests accomplished in both companies have been very satisfactory since an air leak that could not be distinguished by an operator was detected and located precisely.

Experience of use

One ANAES system was installed in C.N. Cofrentes to check that the measured noise was stationary. Six final heads have recently been installed (November 2000) in the same power station and have shown its usefulness detecting a minor intermittent non-radioactive leak.

MALIBA

MALIBA is a teleoperated system with force-feedback. Teleoperated systems are typically used for the remote manipulation of hazardous materials –because of radioactivity for instance–, underwater tasks or in space operations. These systems are composed of a master robot, driven by a human operator, and a slave robot, that performs the desired task remotely. In some cases, teleoperators have force-feedback, allowing the operator to *feel* the forces and torques made by the slave robot on the environment.

In the MALIBA system, the master robot is a closed chain mechanism –a Stewart platform– developed by the CEIT. The slave robot, which is called BTM, is an open-chain mechanism similar to the PUMA 560 manipulator. This robot was developed jointly by ENSA and CASA (nowadays integrated in EADS). The slave robot is able to follow faithfully the movement of the master robot, and the operator can perceive in his hand proportional forces and torques to those that the slave robot exerts on the environment.

A scheme of the complete system is shown in Figure 7. Each of the robots has a controlling computer. Both robots communicate each other through a third computer that also helps the slave computer in evaluating the inverse kinematics. The communication between the slave and the intermediate computer is made using serial protocol RS-232 (115200 baud). On the other hand, the slave computer communicates with the intermediate computer using Ethernet.

The Stewart platform was designed to maximize its dexterous workspace –a subset of the manipulator workspace in which it has a good behavior–. A photo of this prototype can be seen in the left part of Figure 7. Both robots have a force sensor located in the extreme of each manipulator to measure the forces and torques exerted by the operator and the environment respectively. These forces are read using a multiplexer.

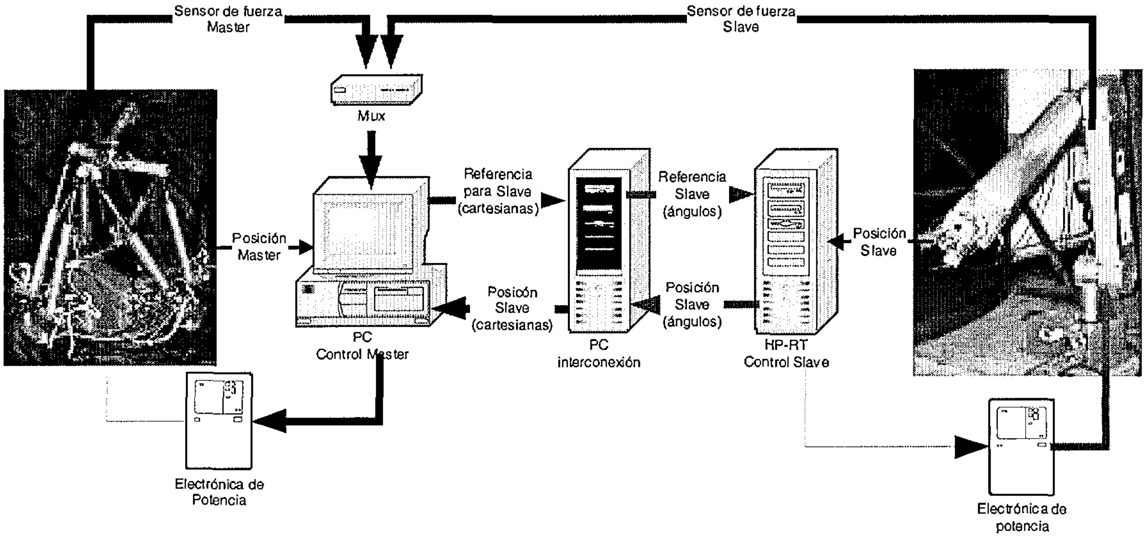

Figure 7. Interconnection scheme plan of the different components of Maliba

The BTM has six degrees of freedom and it can receive position references 200 times per second. This robot has been designed for operation in nuclear power plants and therefore it is prepared to receive high radiation dose.

This system uses a *force-force* control scheme. Hence, both forces in the master and the slave robot are measured and used to generate a reference trajectory that is tracked by joint space PD controllers. To generate the reference trajectory, the movement of a rigid body immersed in a viscous fluid is used. This way, the operator, when handling this system, will fill the same as if he was moving a floating sphere inside a fluid.

Stereoscopic Vision System

After accomplishing the first teleoperated tasks, the need of a multi-camera vision system was detected. With a single camera, it is very difficult for the operator to have an idea of the depth in the viewing direction. In fact, it is practically impossible unless references are available.

The system uses four cameras: one camera integrated within the claw for collecting objects, a field B/W camera and two stereo cameras. The stereo system and the video camera can be observed in Figure 8.

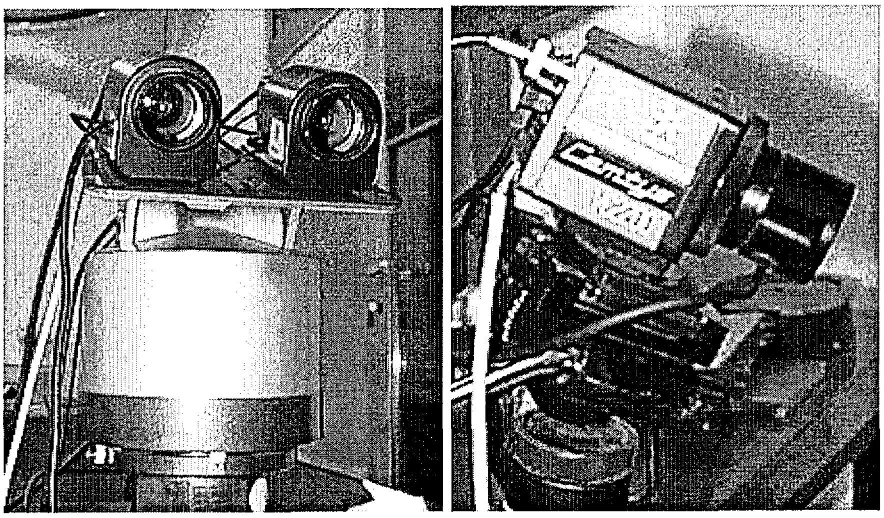

Figure 8. Cameras in the system Maliba

The stereo vision system consists of two cameras with motorized zoom, auto iris and a pan-tilt positioning system. The operator, using polarized glasses, can see in three dimensions in a display with a polarizing filter attached to it. This system, compared to other 3D vision systems, which use active eyeglasses, is more comfortable and allows a longer use without fatigue.

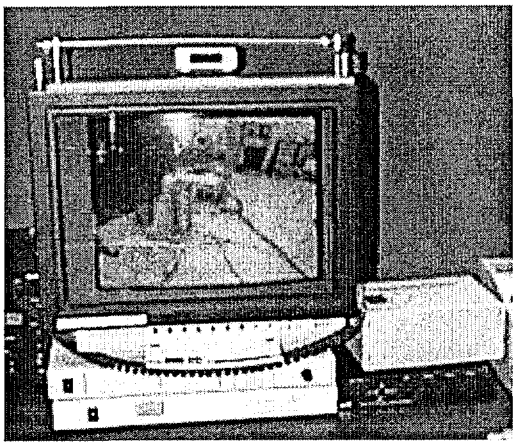

Figure 9. Screen used for 3D Vision.

Tools for the slave robot

Several tools have been developed to demonstrate the capacities of the system. They are an electrical hand with a camera in it, a pneumatic drill and a polisher. These tools can be seen in Figure 10. It is possible to couple additional tools to accomplish other operations.

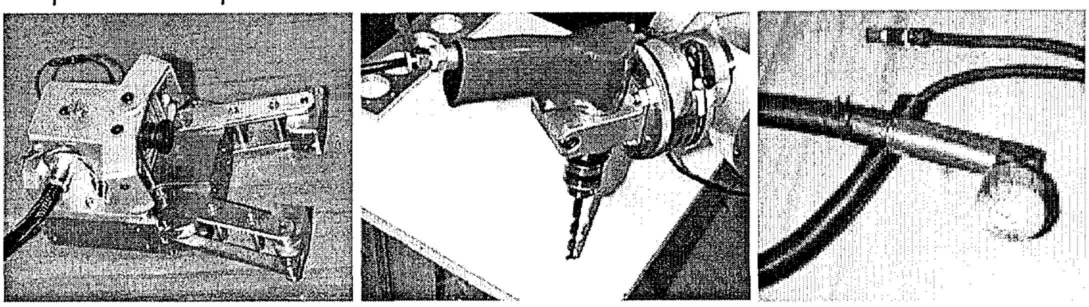

Figure 10. Tools used in the slave robot.

The hand incorporates a camera and several lighting LED's. This camera and the position of the light generated by the LED's, facilitates the collection and handling of the objects.

Conclusions

Even though the developed system is only a prototype, stable and transparent teleoperation has been obtained. The transparency obtained in the different accomplished tasks (withdrawal of objects, polishing and drilling) has been very satisfactory especially in the case of the last operation. Furthermore, the accomplished tests have permitted to test the different potentials of a teleoperated robotic system. Not only as a system that manages distant tasks but also as a system that makes the operations easier than doing them 'in situ' because of force amplification, fixing a direction for the drill, etc.

ROBICEN IV

Robicen IV is the last member of a family of wall-climbing robots designed for inspection in nuclear power plants. The drive unit of Robicen is a prismatic body with electrovalves, ultrasound sensors, vacuum sensors and cameras in it. No electronics –except signal conditioning of the cameras– is installed aboard because of its sensitiveness to radioactivity. A motion mechanism with 2 DOF connects four suction pads with the central body. An unbilical cord that provides compressed air, water, electrical signals and power supply links the robot with a teleoperation station.

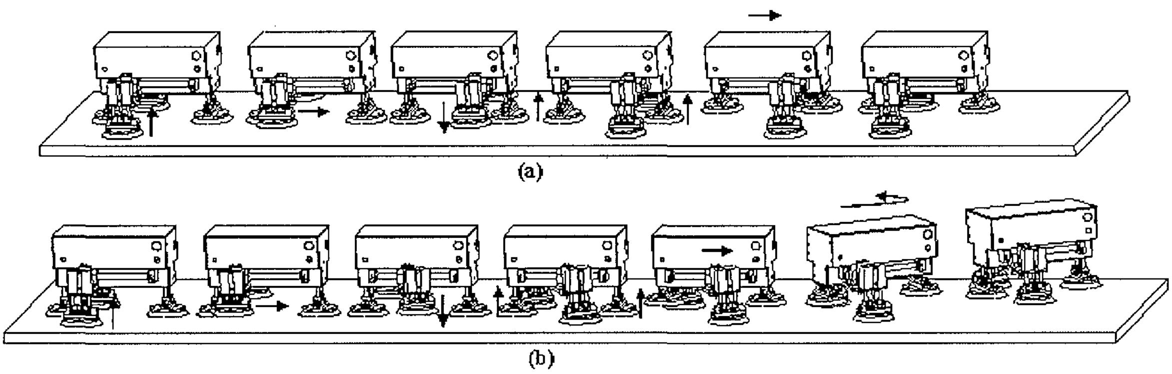

Figure 11 Steps to obtain forward (a) and rotation (b) motion.

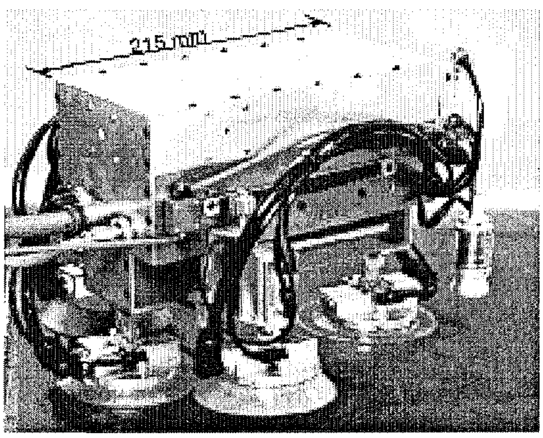

Figure 12 Picture of ROBICEN IV.

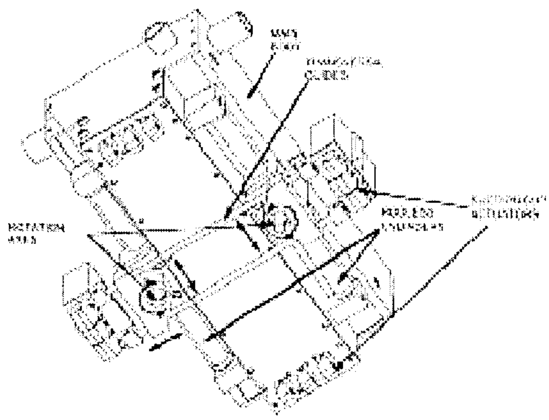

Figure 13 Bottom view of ROBICEN IV without suction pads.

To obtain a forward motion, the two lateral suction cups are simultaneously fixed to the wall whilst the two rodless cylinders are actuated from front to rear, producing a forward motion of the robot's body. Then, the two suctions cups fixed on the main body are simultaneously activated and fixed to the wall. Once the vacuum sensors detect that vacuum has been established, the lateral suction cups are released and the rodless cylinders are actuated to their forward end. By successively repeating this sequence, the forward motion of the robot, depicted in Figure 11, is produced.

To produce a rotation, an analogous sequence of suction cup motions must be produced, but this time the rodless cylinders must be actuated in opposite directions (see Figure 11). Obviously, all elementary motions can be produced in both forward and backward directions.

The robot has proven to be a fast and efficient walker and climber on floor, ceiling and wall, either flat or curved. As depicted in Figure 14, movements over concave and convex surfaces are possible.

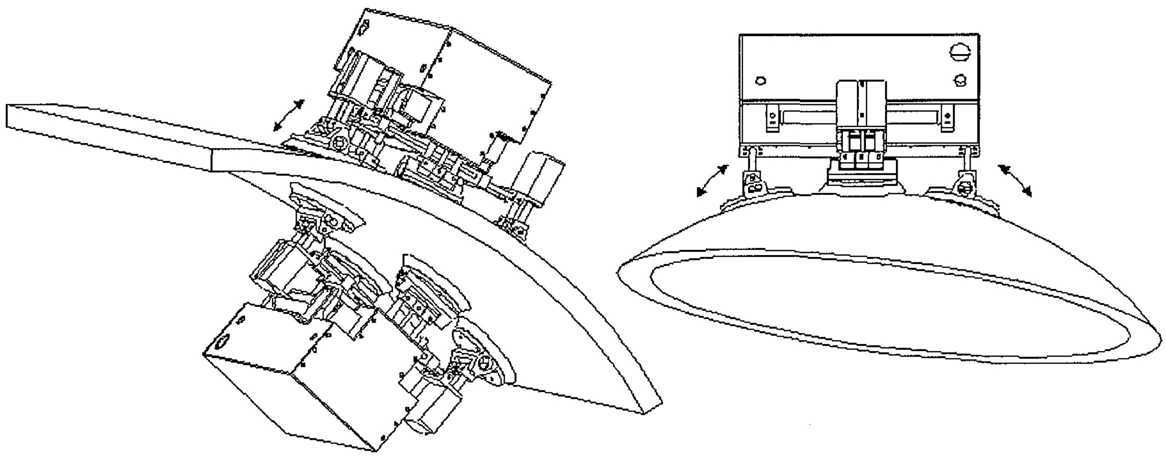

Figure 14 Movement over spherical and cylindrical surfaces.

Vacuum and suction cup positioning systems

Experience gained during the development of earlier prototypes of the climbing robot showed that conventional vacuum generation components, together with commercial pneumatic cylinders, leaded to a system that did not meet the requirement of light weight (under 4 kg). Several commercial vacuum generators were available, but the ones that provided an acceptable vacuum flow had an excessive weight. Therefore, the task of developing a new and more compact vacuum generation and positioning subsystem was undertaken.

With the new approach, shown in Figure 15, two separate vacuum generation systems were fitted under each robot's leg. Vacuum is generated in each suction pad using the Ventury effect. A small vacuum sensor fitted in the body of each vacuum generator checks the adherence force on each leg. Up/down motions of each suction cup are generated by a compact pneumatic actuator composed of a cylinder with two parallel linear guides to provide structural stiffness.

Each vacuum generator is hinged to the up/down actuator. With this freedom for small rotations, each suction cup has the ability to orient in the direction perpendicular to the climbing surface, which allows the robot to climb on cylindrical and spherical surfaces.

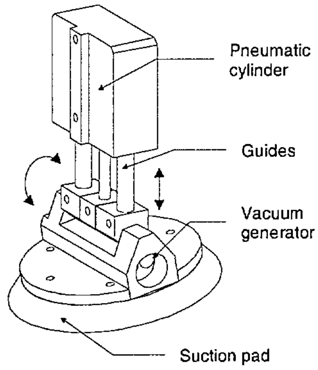

Figure 15 Vacuum system and pads positioning/ orientating system.

Control system

The control system is composed of an onboard controller card based on the 80535 processor. It controls the electrovalves as well as the measurements of the sensors. Although all the electrovalves are of on-off type, each rodless cylinder has a position sensor whose measurement is used in a feedback loop to control precisely the robot's motions.

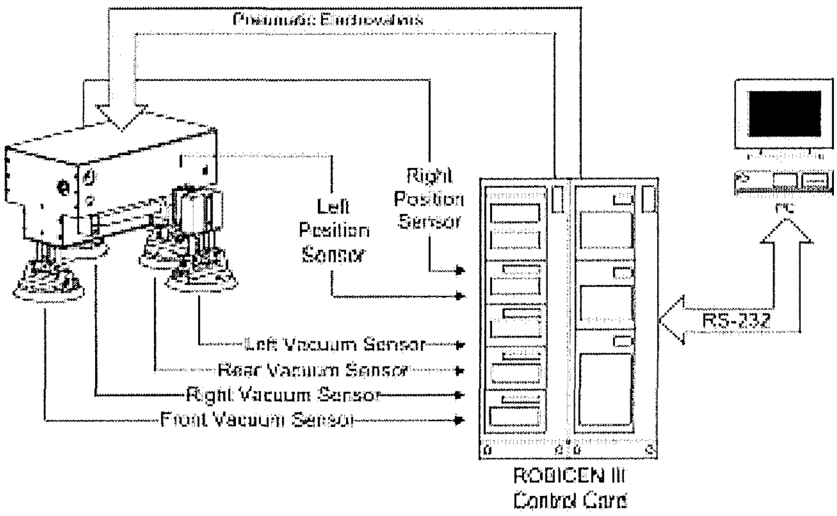

Figure 16 Control signals of ROBICEN IV.

Each suction cup has a vacuum sensor whose measurement is used by the control algorithm to establish whether a step is successful. Whenever a step is considered unsuccessful, it is repeated with successively shorter strokes until sufficient vacuum is obtained. This simple strategy has proven to be very effective, allowing the robot to pass over normal weldings of steel tanks without compromising the robot's safety.

The robot is teleoperated from a PC that sends commands to the onboard controller card through an RS-232 serial port. Since onboard electronics can be damaged by radiation, a version of Robicen IV with a minimum amount of onboard electronics has also been developed.

CONCLUSIONS

Three robotic systems have been presented in this paper: a steam leak detector and locator (ANAES), a teleoperated master-slave system (MALIBA) and a pneumatic wall-climbing robot for inspection of rad-waste tanks (ROBICEN). ANAES has proved to be a useful tool to detect and locate steam leaks in power plants. Its user interface is simple and intuitive and has successfully helped the operators to detect leaks in real plants. On the other hand, MALIBA is a laboratory prototype that has shown the potentiality of master-slave teleoperated robotic systems in maintenance tasks. Additional research is being carrying out in a new project that uses a 7DOF slave robot and a novel cable driven master robot.

Finally, ROBICEN has shown its ability to inspect tanks. The design is intrinsically safe since no step is taken if the vacuum is not guaranteed. Its compactness and lightweight makes it ideal for inspection of inaccessible tanks.

ACKNOWLEDGEMENTS

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