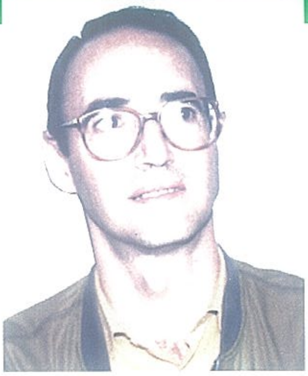


Fernando LINARES is a Mechanical Engineer by Bilbao Polytechnic
1974 Sales Engineer, Northern Region, IROT S.A. (Electronic Instrumentation Manufacturing and Marketing Firm) 1977 Maintenance and Startup Chief, IROT S.A.
1982 Technical Director, IROT S.A.
1984 Assistant to the Instrumentation Department Head in Equipos Nucleares S.A.
1985 Instrumentation Department Head in ENSA
1987 Mechanical Testing Section Head in LABEIN (the Basque Country R&D Laboratory)
1988 Instrumentation and Robotics Department Head in ENSA

DEVELOPMENT OF A GENERAL - PURPOSE MOBILE ROBOT FOR USE IN NUCLEAR POWER PLANTS

A. MARTINEZ - M.A. YAGÜE - F. LINARES

Alfonso MARTINEZ is a Telecommunications Engineer by the Polytechnic University of Madrid.
In 1982, employed by ERIA S.A. to work on UNIVAC computer software design.
In 1983, employed by DIMETRONIC S.A. to collaborate on the development and commissioning of automatic train steering systems.
In 1984, employed by AUXITROL IBERICO S.A. to work on development of supervision, acquisition and control systems for the petrochemical industry.
In 1985, joins the Electronics Division of Construcciones Aeronáuticas S.A. (CASA), to work on different avionics studies and developments.
As of 1988, director of the Automatic and Control Systems section of CASA's Space Division, and has participated in various Robotics and Controller programs.
Currently, Director of the Teleoperated Mobile Robot project.

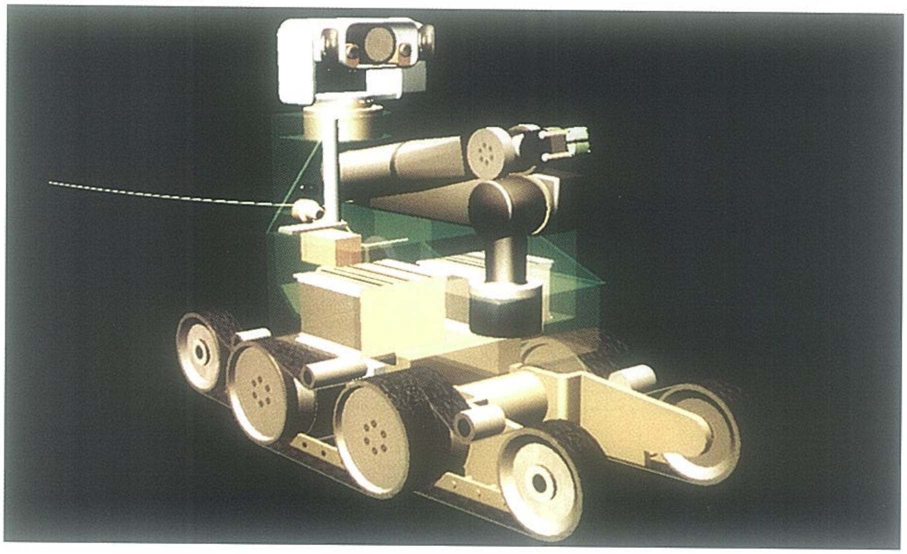
Miguel Angel YAGÜE is a Industrial Engineer by the Polytechnic University of Madrid, specializing in Automatic Systems. Masters Degree in Technical Corporate Management from the 'Instituto de Directivos de Empresa' (Institute of Company Managers).
In 1987, joins the Automatic Systems Department (DISAM) of the Industial Engineering School of Madrid Polytechnic, where he worked on simulation and design of automatic pilots for unstable ship models in the SAEM Project (Automatic System for Maneuverability Tests).
In 1988, joins the SAEM project in CEHP (El Pardo Hydrodynamic Experience Channel, Ministry of Defense).
In 1989, employed by CASA, Space Division, in the Automatic and Control Systems Section, where he works on the AMR (Advanced Mobile Robot) robotics project within the framework of the European EUREKA project. At present, his work focuses on the national TMR (Teleoperated Mobile Robot) project.

BACKGROUND

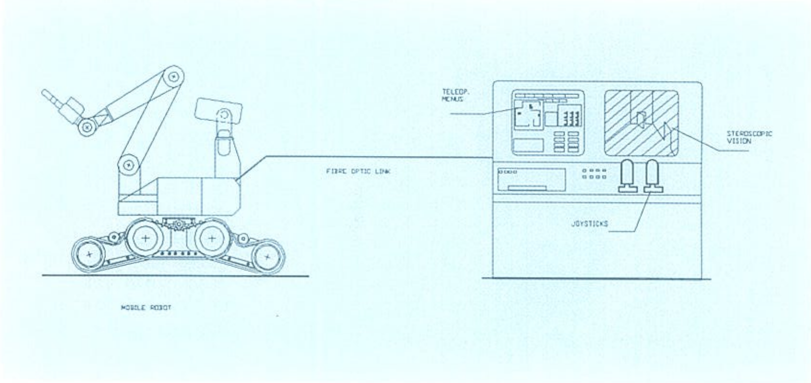
In recent years, the Space Division of CONSTRUCCIONES AERONAUTICAS (CASA) and EQUIPOS NUCLEARES (ENSA) have participated in several national and international robotics programs in the respective space and nuclear areas.
In mid-1992, they decided to jointly undertake the development of a mobile inspection and maintenance robot for Nuclear Power Plants. The success of such a multidisplinary project was ensured by the way both companies complement each other and by their previous developments.
Work was begun on the feasibility study and specifications, for which technical meetings were held with personnel from the Medical and Health Physics Association of the utilities (AMYS) and several Nuclear Power Plants. The result of these conversations was a preliminary system design along with the specifications with which the system must comply.
With these results, a report and job plan were prepared for construction of two prototypes and submitted to the INI (National Institute of Industry Shareholder of both CASA and ENSA), which decided to finance this second Phase of Development by charging it to the Group's Research Development Fund.

PURPOSE OF THE TMR

The tendency of the competent Radiological Protection authorities of the OECD to establish stricter regulations has led to better job planning in Nuclear Power Plants (NPP) and, as a result, a reduction in the collective doses absorbed. This results in enormously improved cost/profit and cost/service quality ratios.
In this respect, there is a growing trend in NPPs to use robots and automatic systems to perform preventive-predictive maintenance, inspection, etc. activites, thus enhancing the integral quality of the service provided.
In view of the above, the purposes of the TMR project are as follows:
- Provide NPPs with a Mobile Robot that can perform Inspection and Support tasks so as to improve service quality by reducing the doses of professionally exposed workers (PEW).
- Provide a versatile tool that can be used in the event of Nuclear Facility incidents, increasing the analysis and performance capabilities during these incidents.
On the basis of data compiled on



F I *TMR Simulation.*



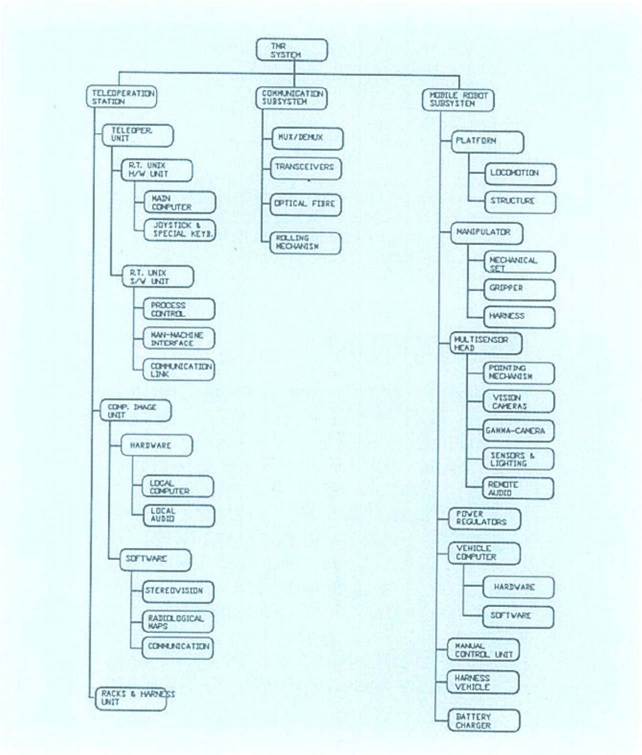
F II *TMR Subsystems*

nuclear environments, it is deduced that main goal, insofar as work automation is concerned, is to reduce the doses received by the PEWs. Therefore, a basic mission has been selected for the TMR that combines all the robot's features and its degree of operability. This basic mission is defined as follows: PREPARE WORKSTATIONS AND HELP IN OPERATIONS

For this mission, it is necessary that the TMR system be a mobile robot with the ability to make observations and measurements, as well as to manipulate equipment and tools. The basic mission includes the following elemental tasks:

- Database generation and operation:
  - Visual maps (mono- and stereoscopic).
  - Radiological maps.
  - Thermal maps.
- Preparation of operations:
  - Training.
  - Preliminary stereoscopic display.
  - Task and exposure time optimization.
- Remote operator assistance:
  - Full duplex audio communication.
  - Job performance viewing.
  - Sensors and alarms.
- Remote inspection.
- Element dismantling.

F III *TMR System Component Elements*



- Cleaning and decontamination.
- Waste collection and storage.
- Element screening.
- Elemental manipulations with the aid of auxiliary elements:
  - •General-purpose gripper.
    Cutting blowtorch.
  - •Industrial vacuum cleaner.
  - •Saw.
  - •Cleaning tools.

TMR DESCRIPTION

The TMR is a mobile robot capable of performing supervision and telemanipulation operations. To perform these functions, a system has been designed with the three following subsystems:

-The Teleoperation Station (T.S.): Located in a low radiation environment from which the robot operators perform teleoperation jobs and receive on going information about the job environment (Telepresence).

-The Mobile Robot (M.R.): Located in the job area, it is in charge of performing the operations commanded by the Teleoperation Station. It is provided with mobility, manipulation capability and sensorization.

-The Communications Sub-system: Responsible for establishing a reliable, full duplex, fiber optic communications link between the T.S. and the M.R.

Figure II shows the overall appearance of the TMR with the three subsystems described above. However, given the intrinsic complexity of each subsystem, these subsystems have been shown in detail (see Figure III) to facilitate detailed description and subsequent functional analysis thereof.

TELEOPERATION STATION SUBSYSTEM

The T.S. performs the basis functions inherent in Teloperation and Telepresence. The T.S. is composed of the following:
a) Teleoperation Unit, T.U.
b) Image Processing Unit, I.P.U.
All the above is integrated into a single, sturdy, easily transportable module. Figure IV shows the T.S. assembly.

a) The Teleoperation Unit, T.U. is based on the following:

- A personal computer 486 with real-time operating system LYNX. The software has C language programming, ADA and user interface through OSF/MOTIF.

The T.U. computer performs the following functions:

- Reads the control board commands.
- Decodes these commands.
- Generates the locomotion control set points.
- Generates the proper set points to control and coordinate the terminal element (grippers) position by means of Cartesian coordinates referring either to the manipulator base or to the terminal element.
- Generates the set points for one-to-one control of the manipulator's six articulations.
- Executes automatic folding and unfolding tasks.
- Executes semiautomatic synchronizing and configuration change tasks.
- Generates the specific commands for controlling the multisensor head position.
- Generates the specific commands for controlling each built-in robot peripheral.
- Periodically transmits the command sequence to the mobile robot.
- Periodically reads and processes the mobile robot's state information.
- Establishes an alarm control.
- Operator-friendly display through the computer screen of information processed in real-time. A window-based man-machine interface is used.
- Generates the specific display, recording and distance measurement commands of the Image Processing Unit.

• An interactive screen that permits the operator to operate the mobile robot and display its state by means of windows.

• The control board with two joysticks (with three degrees of freedom and pushbuttons) and a dedicated keyboard, that permit the operator to control manipulator movements and the platform, as well as the built-in robot peripherals.

b) The Image Processing Unit, I.P.U., is responsible for showing, storing, retrieving and analyzing the images captured by the cameras. In order to enhance the system's ergonomics, stereoscopic vision is provided that gives the operator a greater sense of reality when guiding the robot and inspecting the surroundings. The I.P.U. is composed of the following:

• An operations screen for displaying the selected video signals both in mono-scopic and stereoscopic mode. The 3-D effect is achieved by inserting a polarizing filter between the screen and operator with position adjustment by synchronizing with one of the images displayed on the screen. By using polarized glasses with opposing polarizations in each eye, the operator perceives the sensation of volume. The video system will operate by alternating on the screen the monoscopic images corresponding to the left and right eyes, thus achieving the stereoscopic effect.

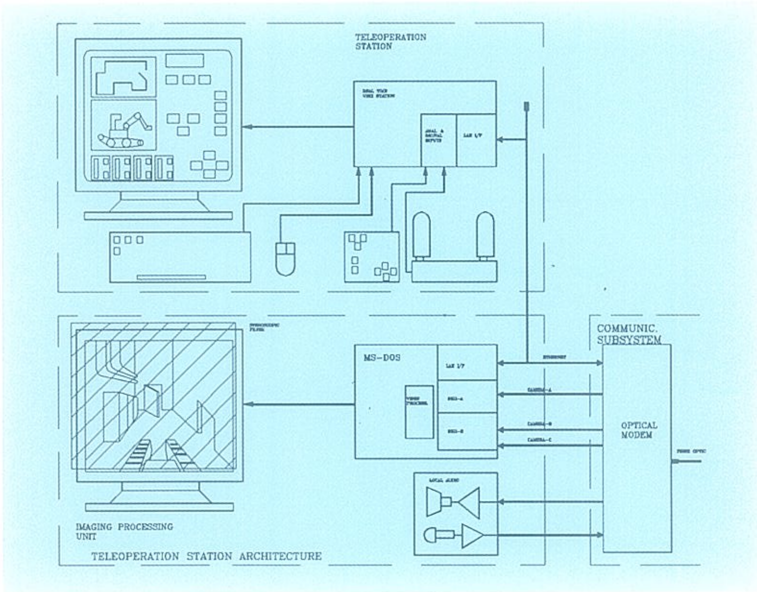
• A personal computer 486 for monitoring control, image processing, and inspection database management. This data bank contains fixed, monoscopic or stereoscopic images resulting from the inspection processes, together with identification data such as date, hour, radiation camera images, etc.

• An independent video recorder for recording the selected moving images.

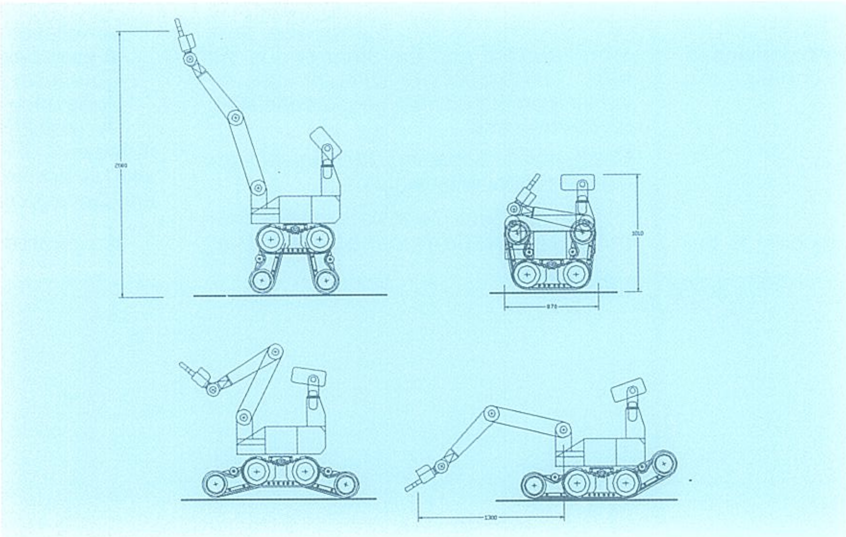
As a result, the I.P.U. screen can display monoscopic, stereoscopic, gripper-camera, and radiation map images.

MOBILE ROBOT SUBSYSTEM

The M.R. is the subsystem that is in contact with the work area and works on it

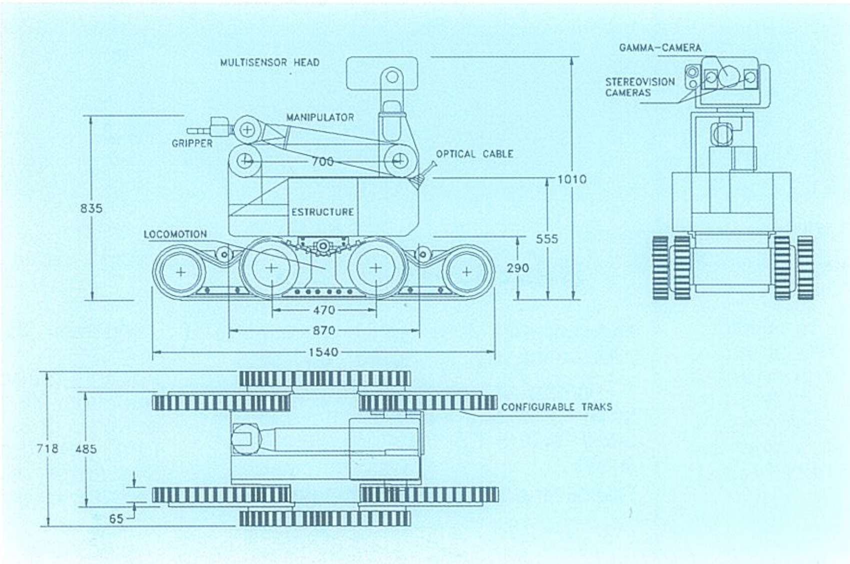


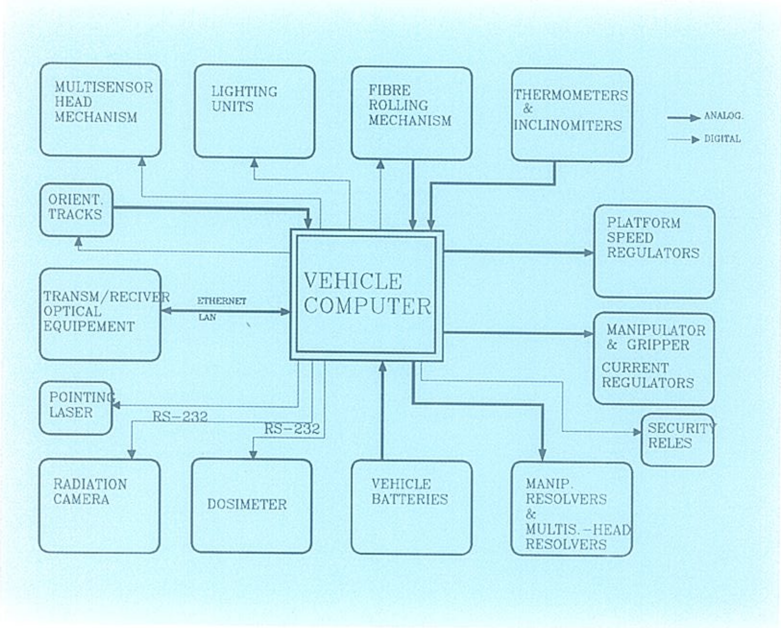
F IV *Teleoperation Station Diagram*



F V *Mobile Robot Configuration*

F VI *Different Positions of the Mobile Robot*





F VII *External Vehicle Computer Interfaces*

by performing the operations demanded by the T.S. To do so, it contains the following elements:

a) Platform.
b) Manipulator and grippers.
c) Multisensor head.
d) Vehicle computer.

a) The platform provides mobility to the robot so that it can clear obstacles and go up/down stairs.

It is also the manipulator's and the turret's mechanical support. The batteries, vehicle computer, optic modem, cable winding mechanism, and locomotion mechanism, all with their respective controls, are located inside the platform.
The platform is divided into two parts:

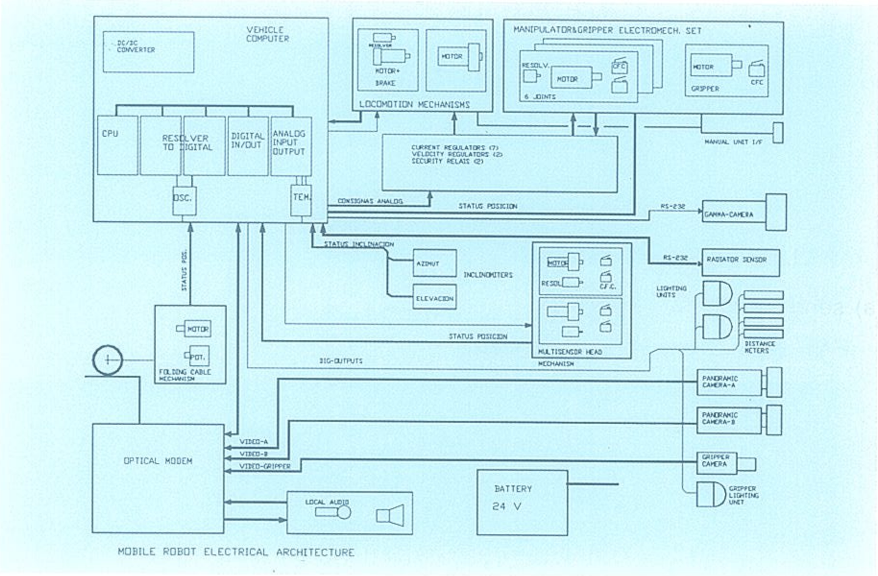
- A locomotive assembly based on a commercial product, with two horizontal and four adjustable caterpillar belts (front/back) driven by electric motors.

- A custom designed structure that integrally supports the manipulator and multisensor head. The structure consists of a set of interconnected aluminum ribs, beams and girders that satisfy the specified, anti-collision rigidity requirements. All the M.R.'s electrical and electronic equipment are housed inside this structure.

b) The manipulator is of the articulated arm type, based on the shape of a human arm with six separately rotated articulations driven by servomotors, which provide six degrees of freedom.
The manipulator is made of several rigid bodies connected in series. One of the chain's ends, i.e. its base, is attached to the platform structure and the other end is left free. The grippers or different tools for working on the environment are installed on this free end.

Mechanically speaking, the manipulator can be divided into two parts:

- Basic chain: consists of the first three articulations called the base,



F VIII *TMR Vehicle Architecture*

shoulder and elbow, which are used to position the wrist in space.

- Wrist: it has three movements - gyrating, raising and rotating - that are used to turn the terminal element in space.

Finally, the six rotary articulations are driven by direct current electric motors through a reducer stage.
The gripper assembly is composed of the following:

- A slender gripper provided with long, thin fingers with torque control.
- A proximity camera coupled to the gripper to obtain perfect vision within the fingers' reach.

c) The multisensor head includes most of the sensors used by the Teleoperation Station operator.
These sensors report on the environment where the robot is working with the following data:

- Vision.
- Distance measurements.
- Radiation index.
- Radiological maps.
- Sound.

The multisensor head is a parallelepiped made of light material (aluminum) that houses the following:
- Two color vision cameras.
- Two spotlights.
- A radiation sensor.
- A loudspeaker and microphoe
- Four laser pointers.
- A distance meter.
- A radiation camera (within the framework of the AMYS-CIEMAT project with financing by the Electric Research and Development Program (PIE))

- An infrared camera.

To make directional measurements with some sensors, an electromechanical unit (electric motor - reduction gear - resolver) is provided that allows the turret to move with two degrees of freedom, azimuth and elevation.
Figures V and VI show the general configuration of the Mobile Robot.

d) The built-in computer is a hardware/software unit based on VME bus architecture with the following missions:
- Control manipulator movements.
- Control platform movements.
- Control the peripherals installed in the robot.

For this purpose, the robot computer receives, decodes and executes the periodic orders from the T.S. and, in turn, periodically sends to the T.S. the most relevant data from the sensors installed in the mobile robot.

The robot computer connections to its environment are illustrated in Figures VII and VIII.

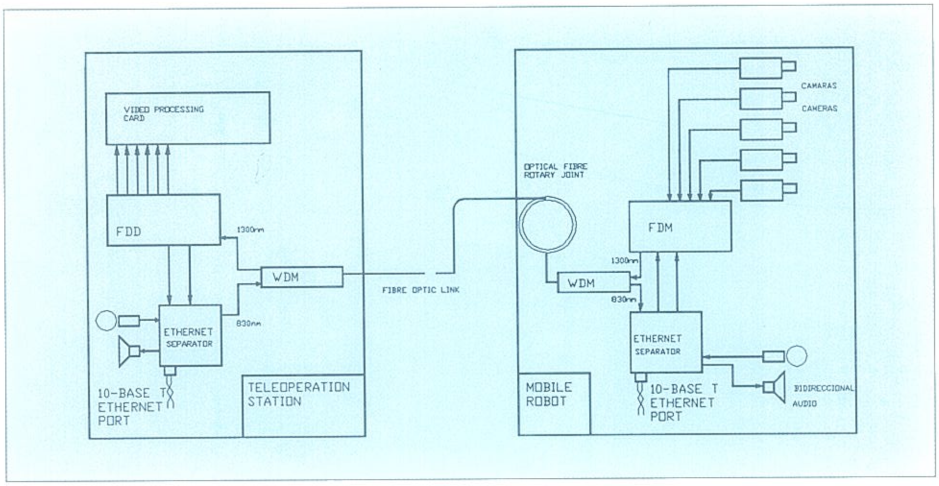
The vehicle computer hardware consists of the following:

- A CPU card with 68030 microprocessor, 25 MHz, serial communication and Ethernet interface.
- An analog I/O card (16 / 16).
- A digital I/O card (16 / 16).
- Two articulation position sensor (resolver) input cards.
- Two custom designed, general-purpose I/O cards.

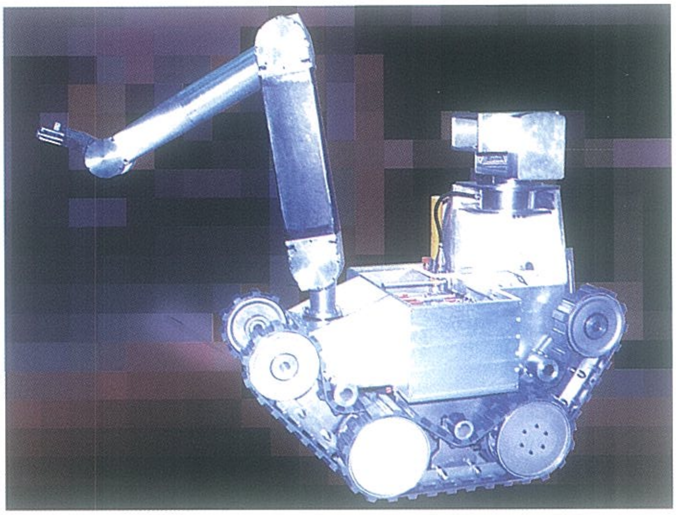
As regards the software, the control program built into the CPU card is executed in a real-time, multitasking environment and makes use of the VRTX Operating System primitives. The C programming language is used to develop the software, which will be located in EPROM memories after a debugging period.

The resident program in the vehicle computer performs the following functions:

- Enables Ethernet network communications.
- Initializes the hardware.
- Receives and decodes periodic orders (50 ms) from the T.S.
- Coordinates control of the six manipulator position servos, generating current set points for the regulators.
- Controls the grippers.
- Controls platform movement.
- Controls the sensor elements.
- Periodically (50 ms) sends sensor data to the T.S.

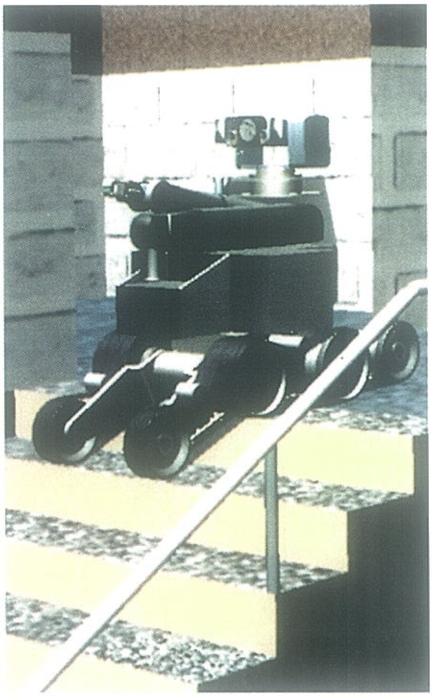


F IX *Communications Subsystem.*



F X (a) *RMT Manipulator.*

F X (b) *RMT climbing capability.*



COMMUNICATIONS SUBSYSTEM

The purpose of the Communications Subsystem is to establish a reliable, full duplex communications link between the Mobile Robot and the Teleoperation Station through a single multimode fiber optic, thus forming a fiber reel that winds and unwinds when following the Mobile Robot's movements (see Figure IX).

To allow this reel to turn, a mechanism has been designed whose components include a Fiber Optic Rotary Joint (FORJ) and an extended cable length sensor. This mechanism maintains a preset tautness for the fiber optic cable to prevent it from getting entangled.

Since only one fiber is used, it must support the communication in both directions, and thus a Wavelength Division Multiplexer (WDM) is provided at each end to separate the light in the two directions, in which it logically travels at different wavelengths. In turn, each wavelength carries signals of all sorts.

From the Mobile Robot to the Teleoperation Station, there is simultaneous transmission of four video channels with a 10 MHz bandwidth, a 20 KHz audio channel, and a fifth video channel for transmitting in one of the Ethernet network directions that provides the high-speed data link between the M.R. and the T.S. All these signals are sent over a wavelength in a second window (1300 nm) by means of a Frequency Division Multiplexer (FDM), which generates a 200 MHz multiplex signal that modulates a 1300 nm laser.

From the Teleoperation Station to the Mobile Robot, a 20 KHz audio channel and the other direction of the Ethernet network are transmitted. These signals directly modulate an emitting LED in a first 830 nm window.

Both ends are provided with corresponding receptor equipment for each wavelength and demultiplexers for retrieving the original signals.

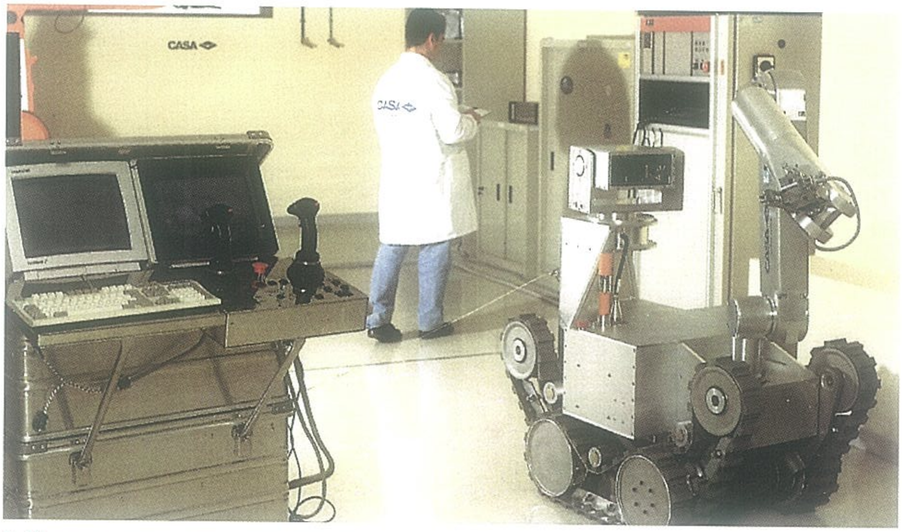
MOST OUTSTANDING FEATURES

The following table shows the general characteristics of the TMR System designed to perform inspection and maintenance tasks in nuclear environments. For greater clarity, the characteristics are broken down by the different subsystems.

MOBILE ROBOT

General Specifications

- DIMENSIONS: (900 x 700 x 1200 mm) (folded); (1470 x 700 x 1200 mm) (unfolded).
- TOTAL MASS:approximately 35 kg.
- TYPE OF TERRAIN: Inside buildings (including paved surfaces, stairways, corridors, obstacles).
- SUPPORTED DOSE: 1-10 krad



F XI *RMT System: Mobile Robot and Teleoperation Station.*

- AUTONOMY:
  - 2 hours with internal batteries
  - Uninterrupted with outside power supply.
- MAXIMUM INCLINATION: 45º
- SPEED: - 40 m/min.

Manipulator and Gripper

- 6 COORDINATED DEGREES OF FREEDOM.
- MAXIMUM RANGE: 1.5 m
- LOAD CAPACITY: 21.5kg centered load; 15 kg with 85 mm eccentricity.
- GRIPPERS WITH TORQUE CONTROL.

TELEOPERATION STATION

- PHYSICAL CHARACTERISTICS: Ergonomic, easily transportable.
- USER INTERFACE:
  - Teleoperation computer (window menus).
  - Control board (joysticks) with dedicated keyboard.
  - Vision computer (with stereoscopic display filter).

COMMUNICATIONS

- FIBER OPTIC LINK, 200 m range (with constant cable tautness).
- SIMULTANEOUS TRANSMISSION CAPABILITY OF:
  - 4 video links (10 MHz).
  - 1 ETHERNET link (full duplex).
  - 1 audio link (full duplex).

Sensors

- VISION CAMERAS:
  - Two cameras on the turret with possibility of stereoscopic vision.
  - One inspection camera in gripper.
  - Directional radiation camera.
  - Navigation camera.
- AMBIENT DOSIMETER.
- INSIDE AND OUTSIDE TEMPERATURE.
- AUDIO EQUIPMENT.
- SPOTLIGHTS.
- DISTANCE METER.
- INFRARED CAMERA.

DEVELOPMENT STATUS AND FUTURE PLANS

At present, work on the Implementation Phase of two operational prototypes is underway. This phase is scheduled for completion in December, 1993. Photographs X and XI show different aspects of the current state of system integration.

Once this basic development phase is completed, specialization and application to Nuclear Power Plants are required. In this respect, the necessary contacts for obtaining the support of the Electrical Utilities have been established. The final goal is qualification of the Teleoperated Mobile Robot in Nuclear Power Plants.