THE HARWELL ROBOTICS PROGRAMME -

TELEROBOTICS PLUS INDUSTRIAL STANDARDS

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ABSTRACT

Two years ago, the Harwell Nuclear Robotics Programme was conceived by consolidating some of the most appropriate technical areas from the existing UKAEA's Active Handling Programme. After a thorough review of robotics technology, several research topics were identified which needed special attention. Communications, servo characterization, robot enhancements, radiation tolerance and systems integration were selected as areas where non-nuclear research was not adequate for successful implementation of robotics to a wide range of nuclear facilities. This paper focusses on these five areas, and describes how industrial standard-based solutions will be examined and applied to active handling equipment.

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INTRODUCTION

For the last 40 years, Harwell Laboratory has been the UK's centre for nuclear remote handling research and development. In recent years, the United Kingdom Atomic Energy Authority [UKAEA] has realized that conventional through-the-wall master slave manipulators [MSMs] and direct viewing may no longer be the first choice combination for active handling, due to more stringent safety requirements.

Future requirements for the nuclear fuel cycle, and other activities such as inspection, maintenance and repair, refurbishment and decommissioning have caused the UKAEA to redefine its strategy for manipulator development. In doing so, cognizance is taken of the recent rapid advances in micro-electronics, computing and robotics, all of which have emerged as technologies in their own right, independent of the limiting constraint of low growth in the nuclear industry. Significantly, by adopting aspects of these technologies, it is possible to design remote handling systems whose components are the result of a much wider development effort, spread across many different industries. In addition, although the UK has developed sophisticated manipulators for gas cooled reactor inspection and repair, it remains unique among the majority of nuclear power states in not having an indigenously produced nuclear servomanipulator. Any new UK developments in computer aided teleoperation are not therefore hampered by established equipment, designed before the recent technology advances. The starting point for the design of a manipulator is considerably different from the baseline drawn 30 years ago, when there was virtually no recognized expertise appropriate to remote handing, outside the nuclear industry.

The Harwell Nuclear Robotics Programme forms a subset of the UKAEA's generic Active Handling Programme.[1] The aim of the Robotics Programme is to identify the rôle that robotic equipment, and the allied technologies such as computing and control, can play in present and future nuclear facilities, and to confirm design predictions by demonstration and installation under realistic conditions. Spin-off into associated areas such as space and "advanced robotics" have ensued.

THE NUCLEAR ROBOTICS PROGRAMME

The Programme is now in its second year. The first year's work consisted of a comprehensive analysis of the enabling technologies for robotics and advanced teleoperation. The technology areas [shown in Figure 1] were chosen to allow the system designer easy access to a structured data base. Because this study was the first-of-a-kind to analyse the UK nuclear industry's requirements, recommendations for development were made for each area. These formed the basis for the present year's research.

Radiation tolerance studies of industrial robots [IR] and their sub-systems indicate that a wide range of peripheral nuclear activities exist which could be carried out with only minor modifications to the robot. Typical tasks such as:

- low and intermediate level waste drum handling
- flask and pipework inspection
- AGR/PWR/FBR fuel fabrication
- filter changing
- posting/bagging-out operations
- decontamination
- glovebox decommissioning
- glovebox operations

require increasing levels of contamination control to be applied, and would benefit from the addition of a real time hand controller for programming or teleoperation.[2] Developments, particularly in the USA,[3-5] support this view. Other modifications, such as the addition of gaiters [booting], or alternative methods of contamination control, and the development of special purpose tooling would also be required.

It is natural to expect that a continued advantage could be gained if it were possible to extend the ability of robots to tolerate more extreme conditions. A robot, by virtue of its commerciality, is an optimized mechanism designed to position and orientate a tool package in space. A basic nuclear servomanipulator mechanism with force feedback may cost three to five times as much as an IR with the same payload and reach envelope [but without force feedback]. Before an IR can match nuclear servomanipulator performance in the majority of applications, deficiencies in the way existing robots are designed and are operated have to be resolved. Secondly, the environmental hazards have to be explicitly described, and thirdly, the tolerance of robotic subsystems to the environment must be understood.

The majority of robotics research is aimed at improving control algorithms or developing exotic sensors for vision, touch and feel. These developments often take five to ten years before they are incorporated into commercially available systems having a proven reliability. Improved control would be of immediate benefit, as it would allow error recovery, collision avoidance, higher level programming and trajectory control using sensory feedback. Model Referenced Adaptive Control Systems ease the computational burden in the robot controller, but are not as yet widely available outside the laboratory. The development of sensors has usually been at the expense of greater complexity at the end effector: this is the antithesis of good nuclear design principles. Most immediately, the required developments are:

- Improving the teleoperator image
  - for successful human intervention and control.

- Force feedback to a master controller
  - for critical operations.

- Design modularity
  - to aid remote maintenance.

- Design for decontamination
  - resistance to acid cleaning and water jetting.

- Standardization of interfaces
  - so that common communications and software can be used.

- Robust viewing and sensing systems
  - to allow adequate control.

Current analysis and hardware development under the Nuclear Robotics Programme centre on five fundamental areas. In addition, complementary work on indirect viewing[6], power and communications, teleoperation and posting, are features of the Active Handling Programme. The areas are:

- Communications, including multiplexing, to reduce cable handling problems for remote manipulators.

- Servo characterization, for cranes, servomanipulators and robots.

- Robot enhancements and design upgrades for operation in radiation environments.

- Radiation tolerance analysis, design and testing.

- Systems integration, to ensure compatibility.

A series of complementary test bed/demonstrator projects are being constructed to establish the information needed to produce viable systems for active plant. Because of the interaction of the enabling technologie test rig evaluation, of for example, an IR controlled by a kinematically dissimilar master arm, would incorporate features such as multiplexing and human factors that will be investigated in their own right on other equipment. Systems integration studies have helped to reduce interfacing inconsistancies to a minimum.

COMMUNICATIONS

As in-cell equipment gets more complex, the burden on the communications system increases. Multicored cables for cranes and gantry-mounted manipulators are already meeting their limits in terms of reliability, ease of procurement, and maintainability. Outside the cell, however, communications can follow non-nuclear practice closely. It is important to make sure that the communications link is transparent to the individual and grouped controllers. The choice of technique and media is strongly dependent upon the partitioning between active and non-active plant areas. The purpose of the research in this subject is to demonstrate compatibility between different manufacturers' equipment and to link together a range of test beds and systems to a central control station which, in some cases, may be up to several hundred metres away.

The systems that eventually will be linked are:

- a gantry crane
- a transporter
- PUMA 560 and 761 robots
- remote viewing systems
- a customized Servoarm [a heavy duty, programmable, teleoperator]
- an electrically linked MSM,

and their systems integration is discussed below.

The emerging Manufacturing Automation Protocol [MAP] standards may be applied to in-cell mobile equipment. MAP benefits from worldwide industrial backing and supports multi-channel video over the same link by using a broadband technique on coaxial cable. However, remote handling activities are unlikely to need all the facilities offered by the full MAP standard. Networking is only required for multi-mode operation with peer-to-peer communications. Mechanical handling will generally need to use the Enhanced Performance Architecture [EPA] for real-time control. Hardware is now available for broadband MAP, but EPA software has not yet appeared in Europe. EPA would be used on carrier-band MAP [the so-called mini-MAP], but this looses the advantage of a broadband medium. The system media chosen for linking the test facilities is coaxial cable using point-to-point modems, and will be used to carry multiple video, audio and full duplex digital links.

SERVO CHARACTERIZATION

The overall aim of this part of the programme is to assess and demonstrate the servo control techniques that are most suited to the wide range of motion control tasks existing in current and future nuclear facilities. Emphasis is placed on the application of present and emerging industrial standards and developments, and on the use of industrial standard components and equipment wherever possible. The phrase "servo characterization" is used to include a number of allied areas within the umbrella of servo control. These areas are:

- Mathematical modelling of servo components, including motors, actuators, controllers and drive mechanisms.

- Modelling of drive transmissions, including non-linearities, loads and disturbances, and their interaction and variability.

- Assessments of static and dynamic performance of servomanipulator and crane servo systems' motion in terms of a range of industrial standard "performance indices".

- An understanding of the servo control techniques relevant to obtaining guaranteed performance from equipment.

- Drive optimization and control system design.

- Development of digital control systems.

- Test bed development for both model verification and demonstration of control designs on representative hardware.

The two key application areas chosen for servo charactrerization studies are bilateral servomanipulator drives and smooth crane control. The bilateral servomanipulator test bed is being constructed around the master and slave arm subassemblies of a commercially available manipulator. This machine can manipulate 8kg and has a 1.5m reach; it was chosen because of its impressive sense of feel and its reliability. Smooth crane control has been demonstrated on a modified five tonne gantry crane which already existed in a development laboratory. The original crane motors and controllers were replaced with brushless AC servo systems, and remote non-contacting position sensing and computer control has been installed. The same crane has been used to demonstrate a robust short range contactless communications system based on a specially developed capacitive transducer. The transducer communicates with a coaxial cable laid along the crane travel, and by segmenting the cable, fail-safe block exclusion zones can be designed into the operating strategy.

The majority of commercially available force reflecting bilateral master slave servomanipulators, developed for nuclear remote handling, use mechanically backdrivable motor-gearbox combinations. This implies the use of a motor with low coulombic friction and starting torque, low gear ratios and transmission designs with considerable backlash, compliance and effective wind-up. Conventional robotic transmissions require mechanically non-backdrivable motions with high reduction gear ratios and low backlash, to ensure repeatable and accurate position control. More recent servomanipulator developments have applied electronic force sensing to master and/or slave arms to either supplement or replace the need for mechanical backdrivability to generate a sense of feel. These solutions do not attempt to match industrial standard component and assembly choices, and are consequently expensive to implement. The test bed will use direct force sensing and industrial standard drive systems to produce high quality force reflection in robotic type joints. The electronically backdrivable joints will have reverse force thresholds [or sensitivities] that will at least match the values obtained by the mechanical linkage or generated by mechanically backdrivable techniques.

Retrofitting motors and sensors onto the gantry crane will provide an opportunity to investigate a range of position sensing and control strategies. Initial positioning uses two multipath distance infra-red measurement systems which can be synchronized to produce co-ordinated motion in two degrees of freedom. The control system allows a selection of preset velocity profiles on both major axes to generate, for example, straight line vectored motion.

ROBOT ENHANCEMENTS

This part of the programme acknowledges that there are many remote handling activities that would benefit from the option of using conventional IR solutions. The radiation tolerance of IRs is low, but can be improved, and real time man machine interfaces are being developed. The large installed base of IRs worldwide means that there is an established infrastructure for service and maintenance, provided any final system retains the majority of attributes possessed by conventional robots. The approach taken is to examine the components of an IR and provide a modification schedule for items which are susceptible to radiation damage, with suggested radiation tolerant equivalents. Contamination control techniques are based on master-slave manipulator experience. An initial design target of an integrated dose of 10^6 rads had been set for the gradual introduction of tolerant IRs.

The Unimation PUMA series of robots is being used to develop this philosophy, partly because of the wealth of data available for the machines from universities and research institutes. An experimental programme has been devised to investigate a range of input devices such as joysticks, trackballs, voice, position and force hand controllers. End effector based sensors using force and vision as the control parameters are being looked at [Figure 2].

It is anticipated that the major method of operating a radiation tolerant robot would be through a workstation which contains all the relevant input and feedback devices. A series of performance tests can be used to validate the correct choice of panel layout, ease of control, ability to perform certain tasks, and adequacy of remote viewing systems. These benchmark tests can be varied to suit specific applications, and the test facility itself is designed to allow a flexible selection of appropriate input/output devices, which are interfaced through an IBM PC-AT and a broadband communications system, to the VAL II controller [Figure 3].

The notional functional requirements of a nuclear robot are:

- very high reliability [MTBF >5000 hrs]
- ease of in-cell service [MTTR <1 hour]
- long service interval [>1000 hours]
- radiation tolerance [>10^6 rad]
- use of industrial components
- industrially supported servicing
- ease of decontamination
- teleoperated and robotic operating modes
- ability to communicate with other plant.

The PUMA test facility also includes a two degrees of freedom transporter which can support an inverted robot. Bulk motion control can be added into the workstation to simulate an in-cell power manipulator equivalent. The added mobility will help in applictions investigations which require gross positioning of a manipulator and co-ordinated motion control.

RADIATION TOLERANCE

Radiation presents the most severe environmental hazard, especially in fuel reprocessing facilities. Here, and during decontamination, the robot might also be heavily exposed to aggressive fluids. Dose rate is particularly difficult to specify accurately in a large facility, as overall beta/gamma activity may vary by about eight orders of magnitude. Those facilities which are concerned with alpha activity generally have low dose rates and total dosages, but require the robot to be designed to avoid contamination carry-over and to be easily decontaminated. The small sizes of laboratory glove boxes may often preclude efficient utilization of robots if retro-fitted. As with the design of an Advanced Manufacturing Technology cell, the robot should be included as an integral part of the handling machinery, rather than as an add-on extra.

Every component of a robot should be examined to assess its radiation tolerance. A value of 10^4 rads is approximately correct for the total survivable dose of an unaltered IR, although the actual degradation might be gradual. Critical items would be:

- encoders [or other transducers]
- any electronics
- organic material
- cable and connector insulation
- seals
- gaitering
- lubricants

Radiation testing allows estimates to be made for these critical items. A comprehesive data base does not exist for all these components, but would be necessary if widespread application of robots in the high radiation environment was envisaged. Data from space, military and accelerator sources is often not relevant because either the irradiation levels or energy spectra are different, or the dose rates do not match those expected in nuclear facilities. Fortunately, robot manufacturers have tended to modularize their products so that it is relatively easy to replace, for example, a motor-gearbox-brake-encoder package as a unit. This means that for the supercritical components a replacement-when-degraded strategy may give up to an order of magnitude mitigation against the total dose limit for the robot.

The radiation tolerance of most important industrial standard electronic components falls as successive component generations achieve higher levels of integration, with semiconductor techniques that appear increasingly susceptible to radiation damage. To compound this problem, these components are being incorporated into existing types of equipment that used to be free from such sophistication. Pressures for increased complexity of plant design naturally look for added complexity in electronics-based equipment, much of which is destined for in-cell use. Unfortunately, the nuclear power industry has such a spectrum of radiation environments that unique solutions do not exist to radiation damage, and particular cases have to be examined in their own right.

Figure 4 shows an example of radiation tolerant electronics design. The split head camera electronics contains the minimum of electronics and has no 'presets' or adjustments: it is essentially maintenance free during its irradiated lifetime. The electronics can tolerate 10^9 rad of gamma radiation with only minor deterioration to horizontal picture resolution [700 TV lines reduced to 650 TV lines]. Dose rates of up to 10^6 rad per hour are possible without significant loss of picture quality.

SYSTEM INTEGRATION

System integration features as part of the programme because of the potentially strong interactions between the development hardware, which needs to be effectively cross-linked. To integrate these separate items of development hardware and to avoid repetition of common tasks, guidelines have been defined for:

- computer hardware
- software
- interfaces
- documentation
- software Quality Assurance Plan

It is also essential to identify all possible future upgrades so that the system architecture can be structured to absorb them at a later date if necessary.

As indicated, the IBM-PC AT has been selected as the standard control hardware because of its good price/performance index. It also has the ability to incorporate high speed array processor boards for tasks which are computationally intensive. There are a significant number of software modules which will be common to most, if not all, of the control systems. These will be written with sufficient generality to satisfy all applications. This approach may introduce a small time overhead but it should reduce software costs significantly. Long term reliability will be improved because of the additional exercise received by the module from running on more than one system.

The complete system will consist of five IBM PC-ATs, all operating as real-time controllers, with each PC running under the real-time operating system MTOS. For a system of such complexity the use of a design methodology for the software analysis and design phases of the software life cycle is essential. To satisfy this requirement, Yourdon's real-time structure techniques are applied with the aid of the appropriate software tools[7].

As already indicated, for part of the initial robot development programme the PUMA robots and their controllers will interact directly or indirectly with their immediate environment consisting of:

- a transporter which provides two additional degrees of freedom
- a stereo TV remote viewing system
- a man-machine interface which includes joysticks, master arm, stereo monitor and VDU.

In addition the future developments will require the PUMA arms to function in close co-operation with an overhead crane and the electrically linked master-slave manipulator. All of these devices will operate remotely from their control consoles. Communication between the control room and the simulated active application area will be via a frequency division multiplexed link. The physical medium, a broadband co-axial cable, permits a future upgrade to a MAP system.

These systems will all work in relatively close proximity to their controllers. To assess the performance of a system operating remotely at a distance of 100m the communication link has been extended to another building. Here a Harwell customized 3 degrees of freedom, hydraulic arm with a lifting capacity of 300kg at 3 metres, Servoarm, will perform tasks as instructed from the remote control room. Two mono CCTV cameras will provide remote viewing.

CONCLUSION

The Harwell Nuclear Robotics Programme has begun to adapt industrial robotics practice to the nuclear environment. The limitations of off-the-shelf IRs are being evaluated, and improvements in the subsystems are being developed to allow a greater penetration of these manipulators into the nuclear industry. The use of standards in procurement which match available industrial equipment will ensure a continuity of supply, thereby reducing the cost of producing small batches of future "nuclear robotic" manipulators. Methods of communication, both in choice of protocol and hardware realization are being investigated to relieve some of the serious constraints posed by the multicore cable which invariably connects the manipulator to the outside world. A variety of test bed evaluations and demonstrator mock-ups are being built to ensure that subsystems can be effectively combined to produce integrated telerobotic active handling systems.

REFERENCES

1. B C SANDERS, E ABEL, M H BROWN, G V COLE, L J WHITE, "An Overview of the United Kingdom Atomic Energy Authority's Active Handling and Robotics Programme", Proc. ANS 1987 International Topical Meeting on Remote Systems and Robotics in Hostile Environments, Pasco, 27 March - 2 April 1987, pp 14-21

2. E ABEL, "Robotic Devices for Future Nuclear Plant?", 24th Plenary Meeting of the CEC Working Group "Hot Laboratories and Remote Handling", Cadarche, 26-28 June 1985.

3. D H NYMAN and T T NAGAMOTO, "Application of Robotics in Remote Fuel Fabrication Operations", Proc. Int. Conf. Robotics and Remote Handling in the Nuclear Industry, Toronto, September 1984, pp 136-140.

4. J J FISHER, "Shielded Cells Transfer Automation", Proc. ANS 1984 National Topical Meeting on Robotics and Remote Handling in Hostile Environments, Gatlinburg, April 1984, pp 139-145.

5. J A YOUNT ET AL, "Conceptual Design Report for a Remotely Operated Cask Handling System", NTIS HEDL - 73767 - Rev 1, September 1984.

6. A A DUMBRECK, C W SMITH, S P MURPHY, "The Development and Evaluation of a Stereoscopic Television System for Use in Nuclear Environments", Proc. ANS 1987 International Topical Meeting on Remote Systems and Robotics in Hostile Environments, Pasco, 27 March - 2 April 1987, pp 106-113.

7. WARD, "Structured Development for Real Time Systems", Volumes I to III, Prentice Hall ISBN 13-854787-4. 13-854795-5, 13-854803-X.

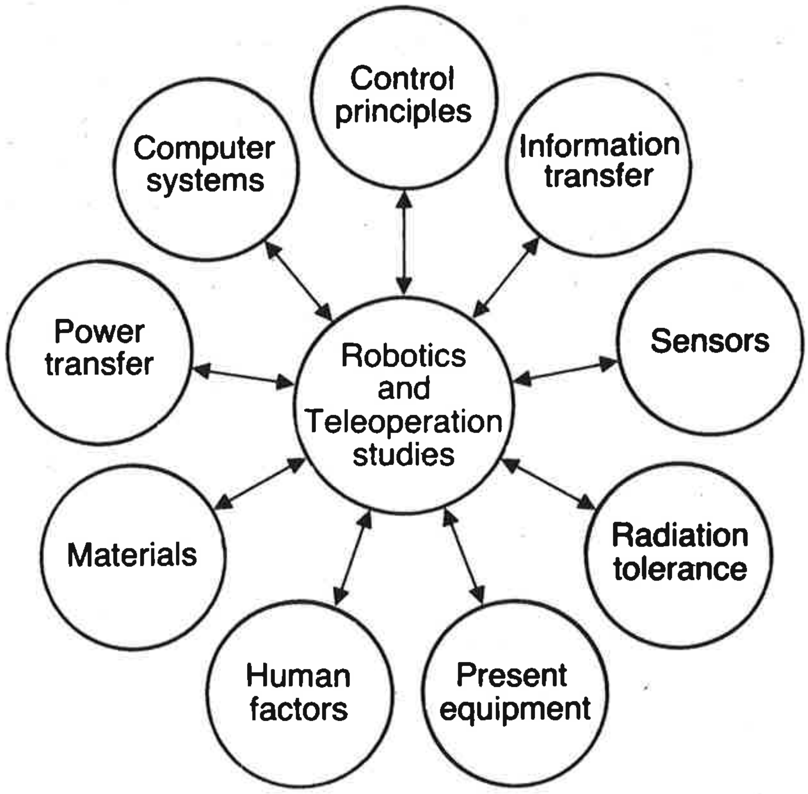

FIGURE 1 - TECHNOLOGY AREAS IN THE ROBOTICS PROGRAMME

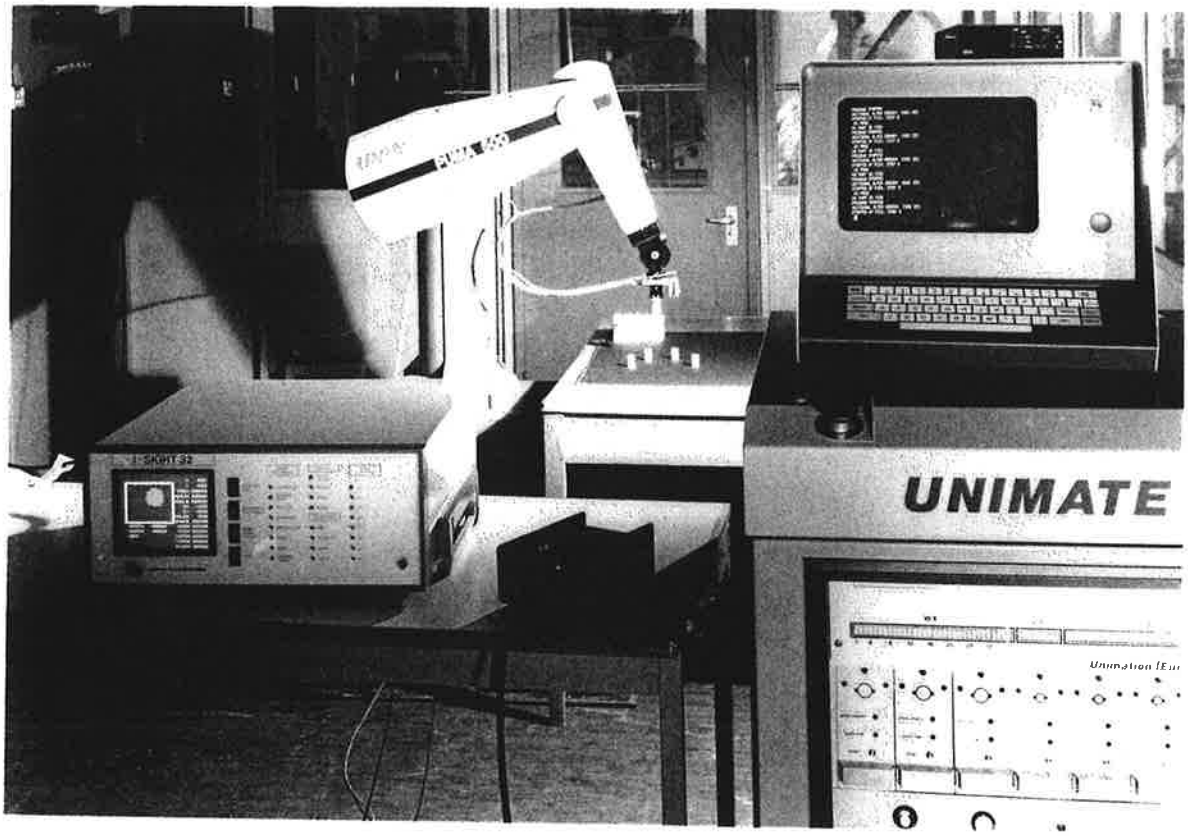

FIGURE 2 - ROBOT PATH CONTROL USING IMAGE PROCESSING

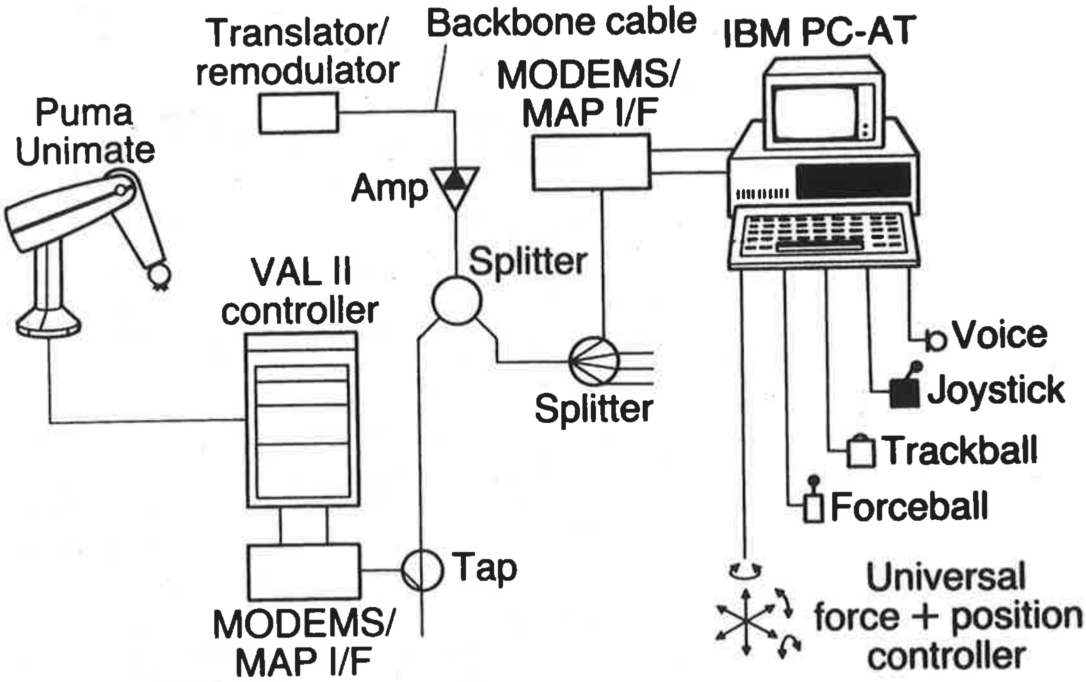

FIGURE 3 - PUMA I/O CONNECTIONS

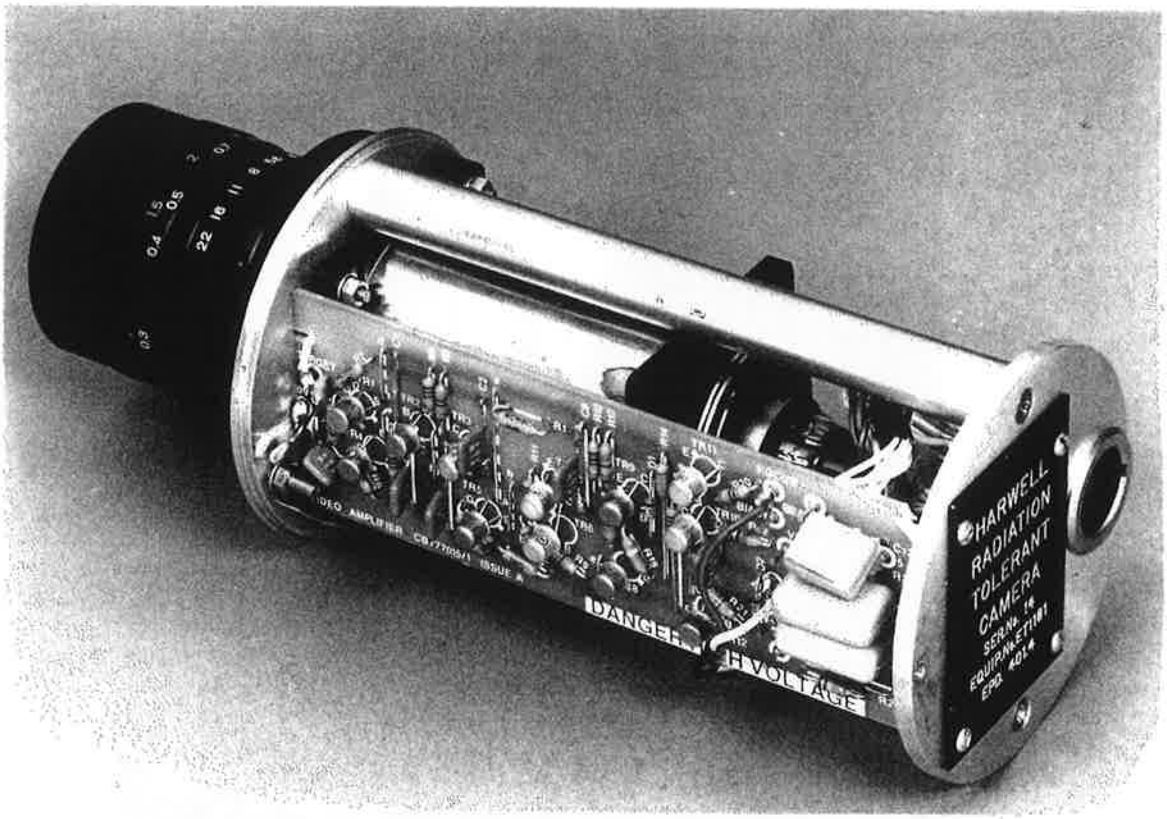

FIGURE 4 - HARWELL RADIATION TOLERANT CAMERA HEAD UNIT