4. Nuclear robotics and remote handling at Harwell Laboratory

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After reviewing robotics technology and its possible application in nuclear remote handling systems of the future, six main research topics were identified where particular effort should be made. The Harwell Nuclear Robotics Programme is currently establishing sets of demonstration hardware which will allow generic research to be carried out on telerobotics, systems integration, the man machine interface, communications, servo systems and radiation tolerance. The objectives of the demonstrators are to allow validation of the techniques required for successful active facility applications such as decommissioning, decontamination, refurbishment, maintenance and repair, and to act as training aids to encourage plant designers and operators to adopt developments in new technology.

INTRODUCTION

1. Conventional active handling activities rely on manipulation based on master slave manipulators, power manipulators, cranes and hoists. As plant has become larger and more complex, and demands increase for manipulative tasks to include maintenance, inspection, refurbishment and ultimately decommissioning, new solutions have to be found that complement existing hardware and will be accepted by plant designers and operators.

2. The Engineering Sciences Division at UKAEA's Harwell Laboratory carries out research into active handling with an emphasis on developing solutions for future plant (ref.1). Within this framework, the Harwell Nuclear Robotics Programme specifically studies the technologies associated with robotics and advanced teleoperation and aims to identify gaps in non-nuclear research which could be critical in adopting effective solutions in nuclear applications. The Programme is complemented by work carried out under other parts of UKAEA's Active Handling Programme, such as research into advanced viewing systems, including stereoscopic television (ref.2) and manipulation (ref.3).

3. Having reviewed the trend of non-nuclear development in robotics technology areas the Nuclear Robotics Programme has focussed attention onto six main research topics. These topics are telerobotics, systems integration, the man machine interface, communications, servosystems and radiation tolerance. These topics are being studied on an individual basis but also form important components of several demonstration projects. The purpose of this paper is to summarize the reasons behind the choice of the research topics, to describe the capabilities of the demonstrator projects, and to show how they can be used to help improve the efficiency and versatility of remote techniques for inspection and refurbishment of nuclear plant.

SOME CONCLUSIONS FROM HISTORY

4. Observations made on the development of nuclear remote handling over the years (ref.4) indicate that the full potential of major innovation is often never realized because the solutions proposed are too expensive, do not address actual requirements, nor can be adequately demonstrated under realistic conditions in mock-ups and active plant. In particular, the development of electrically linked force reflecting servomanipulators is only just beginning to result in machines being designed into operational facilities. The usually long gestation period of active handling systems can be out of step with similar non-nuclear developments, and progress with the balance-of-plant design. The reasons are often that the equipment is special purpose, has some novel features and requires a significant time for testing, performance evaluation, qualification and commissioning. By the time it is ready for deployment, operational objectives may well have changed, along with those users originally responsible for agreeing the functional specification.

5. Project-driven development can avoid many of these pitfalls, because of the close relationship between designer and eventual operator. Generic research is more likely to suffer because objectives are not necessarily allied to specific plant problems. The philosophy of the Nuclear Robotics Programme is to base development and research on non-nuclear industry standards wherever possible, and to devote resources to making systems suitable for the special requirements of the radiation environment. In this way, the Programme can have immediate access to a much greater research effort, and specialize in technologies unavailable elsewhere. The gestation period of new remote handling techniques should be much shorter, and eventual products will be easier to procure because they match conventional industrial practice.

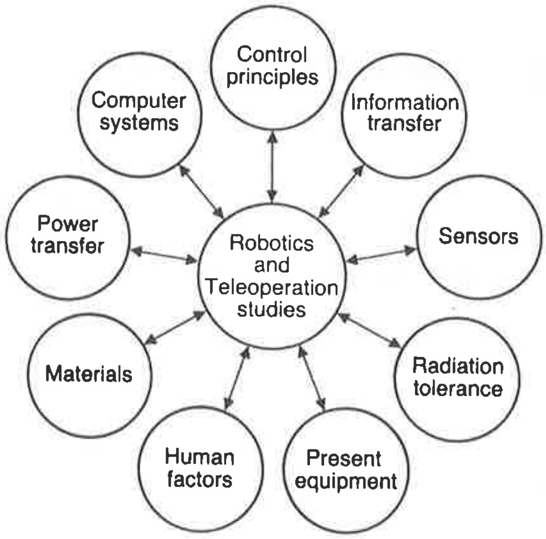

Fig. 1 Technology Areas in the Nuclear Robotics Programme

RESEARCH TOPICS

6. The original nine technology areas (see Fig. 1) analysed in the early part of the Programme have been consolidated to six. As mentioned in paragraph 2, advanced television-based viewing systems, essential features of nuclear robotics applications, are researched in a complementary programme. The six topics are:

- telerobotics
- systems integration
- man-machine interface
- communications
- servosystems
- radiation tolerance.

Each of these topics require developments and techniques that cannot be assumed to be readily available in other industry applications. Often the difference is emphasized by a systems configuration driven by radiation tolerance or contamination control criteria.

7. The research topics are essentially non specific in terms of active handling applications. The aim is that understanding resulting from the research will be useful to any potential application throughout the fuel cycle; because of the difficulty known to exist in gaining acceptance for new technology, the topics will be investigated in conjunction with sets of demonstration hardware, which can also be used to encourage plant designers and operators to adopt the developments in new technolgy. The demonstrators are:

- the Robotics Demonstration Facility
- a teleoperated robot for decontamination and decommissioning
- a remotely controlled hydraulic independent slave arm

Telerobotics

8. Ref.4 highlighted the potential for robotic applications in nuclear plant. A standard industrial robot would not be well suited to nuclear environments. An analysis of a robot which was being considered for reactor decommissioning showed many subsystems that would suffer radiation degradation in operation. Radiation tests confirmed the analysis and no straightforward re-engineering could mitigate against the radiation effects. The robot in question was also needed to operate with a man-in-the-loop, which was a variation which could not be easily accommodated by the control system. In general, robots can be used for active handling, provided care is taken in matching their capabilities to the task, and provided integrated doses are well below 10^2Gy.

9. Our developments in telerobotics centre on adding the features needed to make robots tolerant to the environment and easy to use. A cornerstone of the research is to retain as many of the robot design principles as possible so that the experience gained from production techniques and a large installed base of machines working in varied applications is not lost. The addition of an ability to control a robot's motion in real time, through the use of an input device is essential, and we have developed a series of suitable devices which have been demonstrated on robots ranging from 2kg-20kg capacity. In its simplest mode, the robot can be controlled in either tool or world coordinate systems and a joint by joint control is also possible. The devices interface easily with the standard robot controller, and are based on an IBM PC-AT; the input signals are automatically checked to ensure that servo errors do not arise from exceeding joint angle limits or demanding too fast a response. The PC-AT contains a kinematic model of the robot (in addition to that residing in the robot controller) to perform these checks. The input device can be used to teach the robot if teleoperation is not required. This approach can be faster and more natural than the conventional technique of using the teach pendant. A joystick input device has been supplied to Windscale Laboratory to allow simulation of WAGR decommissioning processes.

10. If a robot can be successfully operated as a teleoperator, which our studies suggest is a valid hypothesis, then the factors which would make it suitable for a nuclear application have great variety. For example, applications may dictate that effective contamination control is more important than radiation tolerance or that decontaminatability is more important than speed of operation. Clearly, to address the needs of applications ranging from fuel fabrication and glovebox decommissioning to PIE and hot cell operations will require a corresponding number of discrete solutions. Even so, a set of key functional requirements for the nuclear industry have been identified as:

- Very high reliability [MTBF of in-cell serviced components >5000 hours]

- ease of servicing [MTTR of in-cell serviced components <1 hour]
- long service intervals [>1000 hours for in-cell components]
- use of industrial components
- contamination control
- ease of decontamination
- radiation tolerance [>10^4Gy for in-cell components]
- industrially supported servicing
- teleoperator and robotic operating modes.

More general requirements for specific applications might be

- load capacity [at least the same as a human's, ie 10kg]
- reach
- ease of use/dexterity
- ability to communicate with other plant.

Each of these functional requirements are being examined in relation to a specific series of industrial robots to establish the modifications needed to produce a prototype nuclear-engineered industrial robot that can also operate as a telemanipulator.

System Integration

11. In some cases the different demonstration hardware will have similar components such as software or subsystems. These potentially strong interactions which may lead to duplicate solutions are guarded against by application of a policy of system integration. Guidelines have been defined for the hardware and software requirements of controllers and their interfaces. Quality Plans and documentation standards have been issued which are common to all developments. The standard control hardware is the IBM PC AT; it has been selected because of its good price/performance index. It is also able to act as host to high speed array processors or arrays of transputers for computationally intensive tasks that have to be executed in short sample periods. By writing software modules with sufficient generality to satisfy a large number of applications, software costs can be considerably reduced. The greatly increased exercising of each software module helps to improve software reliability. Integration of the system just for the Robotics Demonstration Facility requires joining five IBM PC ATs, all operating as real-time controllers, with each PC running under the real-time operating system MTOS. A design methodology is used for the software analysis and design phases of the software life cycle.

Man-Machine Interface

12. As well as the joystick control mentioned in paragraph 9, other input devices are being examined for their suitability. The use of single hand controllers such as the DFVLR and CAE force balls appears to be beneficial, but initial trials suggest that cross coupling effects between controlled axes can give rise to unexpected motions. Both devices allow unilateral operation of a slave arm, but are not easily configured to produce force reflection. Work has begun on developing a general purpose hand controller (ref.5) which is based on the parallel kinematics of the Stewart platform. The mechanism design is compact and easy to service and maintain. It has the potential to be a cheap and versatile input device for teleoperation, and in its basic form can be used as a compound joystick (Fig.2).

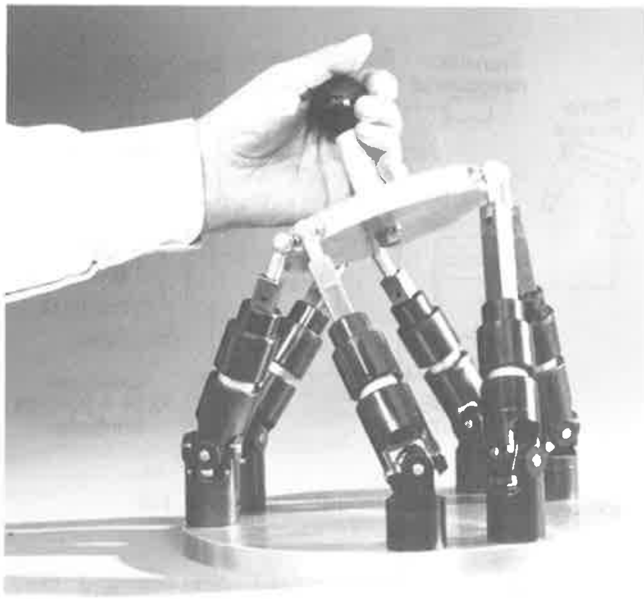

Fig. 2. A Hand Controller based on the Stewart Platform

13. A workstation design can accommodate several different input devices, master arms and television display monitors (including stereoscopic displays). A touch sensitive screen is used to select modes of operation and a task box designed to present typical manipulative tasks to human operators will feature in human factors and visual perception studies in the Robotics Demonstration Facility.

Communications

14. As in-cell equipment becomes more complex, the communication load increases. Multicored cables for cranes and gantry mounted manipulators are already meeting their limits in terms of reliability, ease of procurement, cost and maintainability. Existing cell structures are usually optimized to reduce unused space, and access to gantries can be difficult, which poses special problems when considering refurbishing present plant. Outside the active area, however, communications can follow non-nuclear practice by using standard communication hardware and protocols. It is important to ensure that the communication system is transparent to individual controllers. The use of a broadband cable in the Programme allows a common communications strategy to be used throughout. Point to point modems link equipment, and multiple video, audio and full duplex digital data can be transferred around

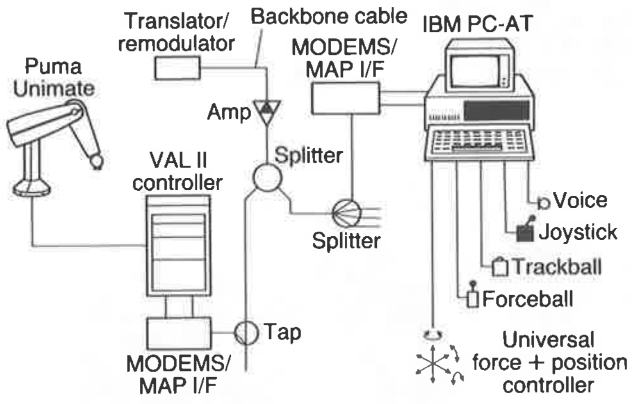

Fig. 3 Use of the Broadband Cable for Communications

the system. The robot input devices and their PC-based controller are linked to the robot controller via the broadband cable (Fig.3) which can be used to support MAP associated Enhanced Performance Architecture hardware for real-time control if required.

15. Currently, camera systems for radiation environments tend to use twisted pair signal transmission. A study has looked at the techniques for radio frequency communications, and in particular has examined alternatives such as bus bars, non-radiating and radiating leaky feeders and pseudo free-space transmission with non-directional or directional antennas. Some of the candidate options will be tried and evaluated on the Robotics Demonstration Facility.

Servo Systems

16. The overall objective of servo system development is to assess and demonstrate the servo control techniques that are most suited to the wide range of motion control tasks that are encountered in teleoperation and crane transmissions. Emphasis is placed on the application of present and emerging standards, and includes modelling, simulation and optimizing the control system, drive components and servos. Digital control techniques are now coming into widespread use, but their performance depends on the quality of measurement of position, velocity and acceleration. Robust sensors are needed that are compatible with the active environment, and system solutions are being evaluated on test beds to establish the validity of simulations, and to build up data on which control strategies can be based.

17. Smooth crane control has been demonstrated on a refurbished 1952 5 tonne crane. The long and cross travel motors were removed, and replaced with brushless AC servo motors (Fig.4). Position measurement of long and cross travel was achieved by using two infra red electronic distance measurement systems which were located at ground level and whose beam paths were directed by mirrors and retroreflective elements. Despite the age of the crane and its original transmission elements, repeatable

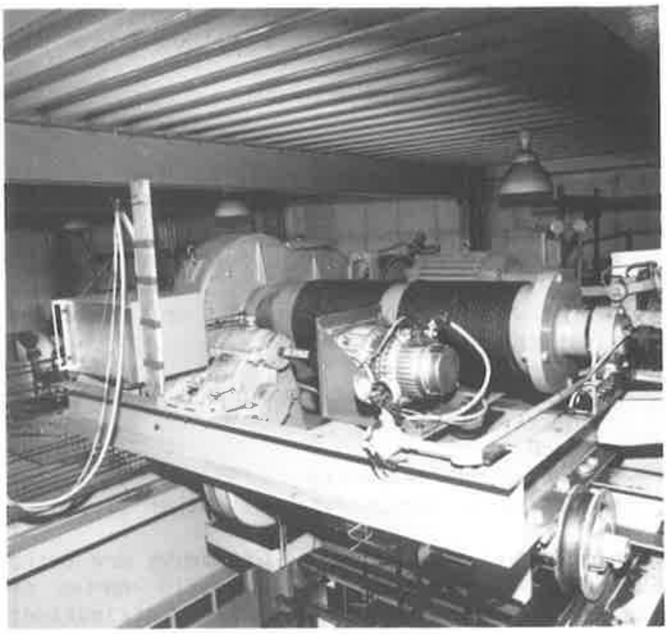

Fig. 4. Retrofitted Cross Travel Motor.

controlled motion and positioning of the long and cross travel has been possible by using a digital motion controller. Creep speeds of a few millimetres per second and bumpless reversability has been shown. The hoist motor will soon be replaced with an AC servo motor which is rated to maintain the crane rated load of 5 tonnes in suspension without application of mechanical brakes. Active compensation of hook heave motion and hook swing is planned. The dynamics of the hook motor have been simulated and its performance and precision of simulation will be confirmed through experiments with the motor mounted on a test stand.

18. Several experimental manipulator powered joints have been produced with different torque ratings and gear ratios. The principle of an electronically backdriveable high gear ratio powered joint has been demonstrated for a prototype bilateral servomanipulator test rig, and special purpose motors have been designed and built for the evaluation of force reflection through direct drive master arm joints.

Radiation Tolerance

19. Radiation effects on system performance can be difficult to quantify. Shielding calculations in general do not consider the migration of contamination within cells, and data on activity distribution within shielded enclosures is limited. Across the range of active handling facilities overall beta/gamma activity may vary by eight orders of magnitude. As more reprocessed fuel enters the fuel cycle, handling equipment in gloveboxes will also need to be assessed for radiation tolerance as well as the more conventional criteria of contamination control. Within the Programme, radiation tolerance studies include subsystem and component testing and redesign to suit a level of radiation tolerance. The testing and literature reviews form part of a data bank on

radiation damage mechanisms, device performance and degradation mechanisms (ref.6). An early design of a radiation tolerant [10^7Gy] camera with a split head has recently been upgraded to include a remote scan drive circuit and presently available tubes.

20. The redesign of a series of industrial robots (paragraph 10) for radiation environments requires a complete examination of subsystems and components. The analysis indicates that the major constraints on redesign are in obtaining a consistent accountable source of components and materials which can be built into the nuclear robot with some guarantee for success. Radiation testing has shown that devices with the same electrical characteristics and type number, but sourced from different manufacturers, can have a tremendous difference in the onset of degradation. Almost certainly, device selection will be based on a statistical technique associated with batch testing.

THE DEMONSTRATORS

The Robotics Demonstration Facility

21. This facility consists of a demonstration area with a control room at each end. An inverted PUMA 560 robot is suspended from an X-Y gantry system, which can move the PUMA at speeds of up to $0.5ms^{-1}$ in the 6x3x2m working volume. In the working volume of the gantry is a floor mounted PUMA 760 robot (Fig.5). Above the gantry is a computer controlled 5 tonne crane (paragraph 17) with a positioning accuracy of 1mm. Mono and stereo camera systems are linked through a broadband cable system to one of the control rooms where a workstation has been designed to accommodate a selection of cctv monitors and man machine interfaces. A hierarchical control system is distributed over the broadband network with a top level control computer which issues system level instructions to lower level subsystems controllers. The facility provides the communications test infrastructure, the hardware for realistic demonstrations of the principles of teleoperation using industrial robotics and a variety of input devices, and an arrangement for the examination of system level strategies such as cooperation, collision avoidance, cell management and sensor data fusion.

A Nuclear Engineered Teleoperated Robot

22. Decontamination and decommissioning are just two of many different applications which would benefit from the introduction of a nuclear engineered robot design. Bearing in mind the Programme developments in telerobotics (paragraphs 9-10), application studies have examined in detail the way in which a prototype device could be effectively deployed, and the engineering implications for plant operations. The prototype robot will be used to confirm the predictions made by simulation of the task and to assist task definitions. One recent example of an application study concerned the decontamination of the insides of stainless steel boxes used as refurbishable containments for chemistry experiments. The stainless steel boxes are removed from their shielding and moved to a shielded refurbishment bay. Hot spot monitoring and selective electrochemical decontamination could reduce background levels to allow man entry for refitting, and a simulation was performed using GRASP, a robot kinematic and solid modeller. The simulation modelled a PUMA robot with special tooling which was introduced into the box through a rear door; additional degrees of freedom were needed to transport the robot into the box (Fig.6). The simulation showed that the initial choice of robot size posed difficulties in trying to perform sequential decontaminations because some required motions exceeded joint limits. A revised simulation selected another size of robot which was then seen to perform adequately throughout the box volume. Similar studies and practical trials are presently underway investigating the use of the prototype robot for decommissioning.

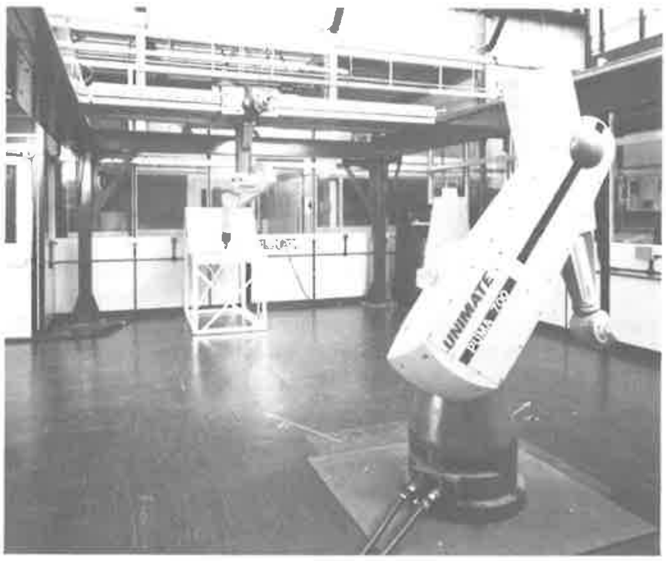

Fig. 5. The Robotics Demonstration Facility

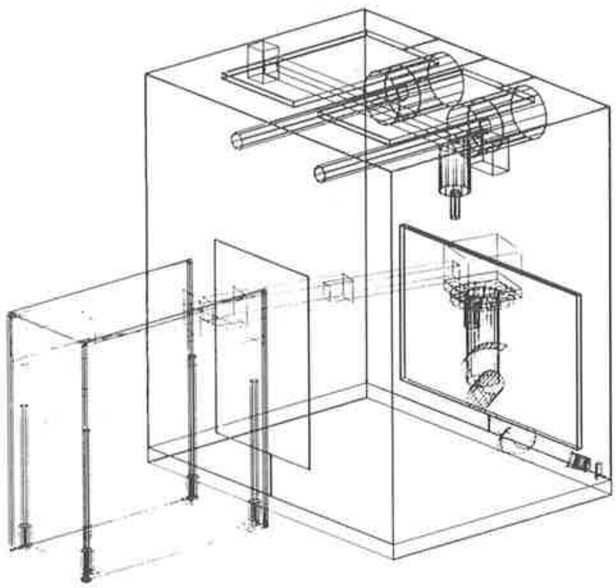

Fig. 6. GRASP Simulation

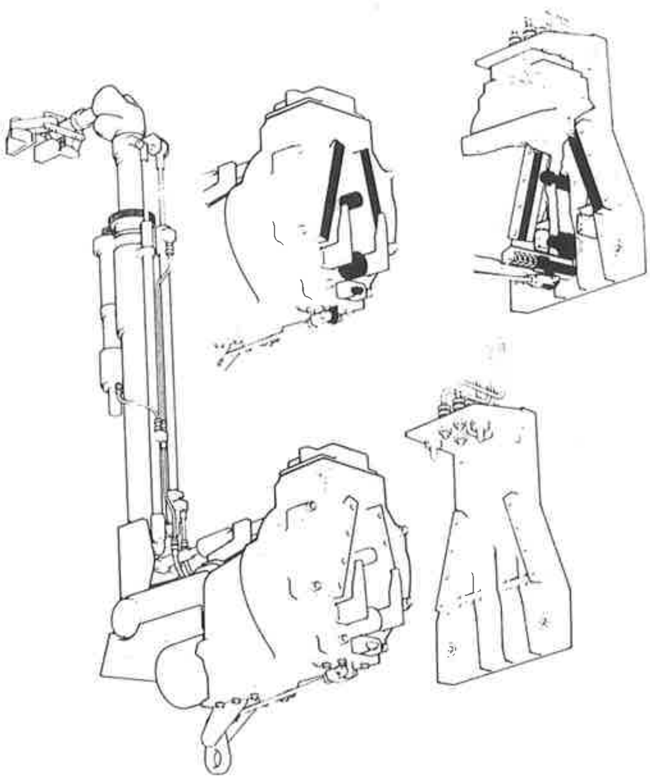

Fig. 7. The Remote Independent Slave Arm

The Remote Independent Slave Arm

23. The Remote Independent Slave Arm [RISA] is a continued development of the Harwell hydraulic manipulator, with force feedback. Local and remote [over 400m distant] work-stations will allow control of the slave arm using a single broadband cable communications network. Feedback of stereo vision, force and other kinaesthetic cues will be frequency-division multiplexed over the cable. RISA will consist of a hydraulically powered slave with electrical and hydraulic connectors that can be automatically connected as the arm is lowered onto its mounting plate attached to a cell wall. (Fig.7). The concept allows plant flexibility in that the manipulator can be placed exactly where it is needed rather than in some permanent position. The use of an electric master arm means that force feedback control is possible, and one master can be used to service several slaves, in sequence, if required. This demonstrator will allow an evaluation to be made of realistic remote handling, communications techniques and workstation design.

CONCLUSIONS

24. The Nuclear Robotics Programme is developing some of the generic techniques needed for manipulation in the nuclear industry of the future. With the use of simulation to predict behaviour of systems, and demonstration hardware to validate simulation and on which to base specific experimentation, designers will be able to become familiar with the new techniques that are arising from outside the nuclear industry, in automation, communications, robotics and control. Work so far has concentrated on improving the man-machine interface for industrial robots so that they operate efficiently as teleoperators. Application studies into decontamination and decommissioning have established the suitability of the approach. Future work into remote workstation design, systems integration and implementation will establish the ground rules for effective systems configurations based on truely remote handling.

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