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NUCLEAR ROBOTICS RESEARCH AT UKAEA's HARWELL LABORATORY

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ABSTRACT The Harwell Nuclear Robotics Programme uses demonstration hardware to validate generic design principles and to explore systems integration issues before active plant design and trials begin. Three activities are described. A prototype nuclear engineered telerobotic manipulator, based on an industrial robot, is being designed and constructed. This low cost device will be of use in decontamination, decommissioning and waste handling tasks, and several application studies and trials have been completed. The Robotics Demonstration Facility includes a computer controlled 5 tonne crane, a gantry mounted robot and a floor standing robot. Both robots can function as telerobots using a specially designed input device controller, and have overlapping workspaces. A remote hydraulic independent slave arm with force feedback and connection to local and remote [>400m] workstations through a broadband communications link is the next stage of development of the successful Harwell hydraulic manipulator.

INTRODUCTION

The initial objectives of the Harwell Nuclear Robotics Programme have been previously described.[1] Work now is underway, focusing on demonstration hardware and construction, to closely match possible applications in active plant. The emphasis of the Programme is to use demonstrators to validate generic design principles and to explore the systems integration issues. This approach is consistent with our experience of remote handling research and development, and is even more important as equipment becomes more complex. Plant designers and operators need sufficient practical proof of new techniques before they can be incorporated into active plant proposals or pre-construction pilot studies. The demonstrators therefore will have the dual function of being a research test bed and a potential training aid.

At the heart of the development is the production of a prototype nuclear engineered robot, based on an existing commercially available machine. The Nuclear Engineered Robot [NERO] will use the standard robot controller, to which has been added a specially developed joystick input controller, so that efficient teleoperation can be accomplished. The prototype is being engineered to allow an evaluation of its performance to be carried out in an active environment, proving the ease of maintenance and reliability of subsystems and establishing the design criteria for future plant applications. In parallel with the NERO development, work on telerobotics, systems integration, the man-machine interface, communications, servosystems and radiation tolerance is carried out, mainly on hardware in the

Robotics Demonstration Facility [RDF]. An important complementary programme on remote television systems is reported elsewhere,[2] as is specific work on force feedback for the Harwell Hydraulic Manipulator.[3] The continued development of the hydraulic manipulator includes the production of an independent slave arm which will be remotely controlled, and will embody many of the communications and workstation design principles established by the RDF experimentation.

This paper describes the progress made so far in the Programme, and the various research topics. The demonstrator projects provide an ideal mechanism for increasing the efficiency and versatility of remote handling equipment to meet the UKAEA's future requirements.

NUCLEAR ROBOT DEVELOPMENT

Background Mechanically linked master slave manipulators (MSM) and power manipulators are the mainstay of remote handling equipment in existing and currently planned nuclear facilities. MSMs, especially, restrict operators to the cell face, are easily damaged and can be difficult to maintain. Their design principle has remained much the same over the last 40 years despite changes in facility size and complexity, more stringent Health Physics requirements, and advances in non-nuclear handling techniques. Attempts to replace the MSM with electrically-linked force-reflecting bilateral servomanipulators in the 1960s failed because of the high unit cost of those manipulators, a perception of unreliability in electronics hardware, and an unwillingness to adopt new technology despite the advantages of increased volume coverage, a more adaptable mechanism and a design less prone to operator abuse. The development of force reflecting servomanipulators continued in several national laboratories and companies, and commercial systems are available now. Their costs range from £0.2M to £1.8M for a basic machine, and except for very specific applications such as accelerator target maintenance or fusion research, operational experience of production quality machines [rather than prototypes] is non-existent.

In contrast, development and progress in robotics has been dramatic. Robotics technology is driven by market forces which have resulted in mechanisms and controllers that are reliable, cheap, easy to maintain, and have operational experience of tens of thousands of hours per model. Worldwide, there are over 100,000 operating industrial robots. One of the major conclusions of an internal UKAEA study has been that many of the attributes of an industrial robot could be directly matched to the requirements of nuclear remote handling equipmment.[4] The most obvious deficiencies of industrial robots were their lack of radiation tolerance, and lack of an effective teleoperator interface - to allow real time control by a human operator. Other differences, compared to an MSM, are the relative manipulator size and stiffness for a given payload, but these factors give advantages of robustness and ease of maintenance. Although the replacement of MSMs by industrial robots in existing plant is not generally viable [mainly because the space available for deployment and maintenance is limited], many applications such as decontamination, decommissioning, waste handling and packaging, fuel fabrication and reprocessing, posting, inspection, maintenance and repair could be configured to use suitably modified industrial robots. If the modifications do not significantly change the engineering of the industrial robot, then the industry can benefit from the accumulated experience of non-nuclear applications, and as significantly, benefit from the economies of scale that result from an established robot manufacturing route.

An alternative to modifying industrial robots is to build special purpose servomanipulators, and specific examples in the UK are CEGB's WARRIOR, GEC's Advanced Slave Manipulator, and the WAGR decommissioning manipulator. The disadvantage of these machines is that they are so special, and do not have experience behind their design from a significant operational history. Their costs are comparatively high and the ability to repair and maintain contaminated machines effectively is unproven. If the nuclear industry wishes to reduce the lifetime costs of remote handling equipment, the benefits of adapting a mature series of robot designs which are supported by an established manufacturer will be significant. Our Programme plans to demonstrate that such an option exists by re-engineering an industrial robot in association with the manufacturer, to suit a range of nuclear environments, and in addition, provide an effective teleoperator interface and communications infrastructure. The Nuclear Engineered Robot [NERO] will first exist as a prototype but will be the baseline design for commercially available versions. The prototype is based on the Unimation PUMA 762 robot, with a 20kg capacity.

Robot Requirements 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 decommisioning 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 >5000hrs]
- ease of servicing [MTTR of in-cell serviced components <1 hour]
- long service intervals [>1000 hrs for in-cell components]
- modularity
- use of industrial components
- contamination control
- ease of decontamination
- radiation tolerance [>10^4Gy for in-cell components]
- industrially supported servicing
- teleoperator and robotic modes.

Special applications might also specify

- load capacity [10kg minimum]
- reach
- ease of use/dexterity
- standard communications protocols

Typically, because robots are used in production plant where downtime is unacceptable, reliability is high, despite a variety of attitudes to maintenance procedures. The prototype NERO will exhibit a similar potential for reliability to the mother design because the overall mechanism and transmission design has not been radically changed. Servicing has been examined with respect to glovebox or suited working resulting in modifications to fixtures and fastenings. The radiation tolerance has been enhanced by developing radiation tolerant subsystems where necessary. External surfaces are smooth and tolerant to washdown and swabbing, to allow decontamination, and additional seals and cover redesign has been undertaken. Finally, an interface to the robot controller allows hybrid teleoperation and robotic operating modes.

Teleoperation So far we have produced a versatile teleoperator interface for the PUMA 560, PUMA 761 and PUMA 762. The payload range for these machines is 2kg to 20kg. We have carried out preliminary manipulative trials using the interface shown in Figure 1 with two three degree of freedom joysticks and a six degree of freedom hand controller. A version 2 joystick interface has been shipped to UKAEA's Windscale Nuclear Laboratory to allow control of their PUMA 762 machine as a teleoperated manipulator to simulate decommissioning operations. Version 2 incorporates teach and repeat, operation in world, tool or joint co-ordinate systems, and a touchscreen is used to select the operational modes. Through the menu, the robot arm power can be dis-

Figure 1. The Harwell Input Controller

abled, the touchscreen can be calibrated, and tool offsets can be set. Normal features such as inserting, modifying or deleting VAL instructions, moving through and editing programmed points, merging joystick instructions and replaying the result are included and accessed through the controller. Automatic checks are made of the demanded command parameters for legality against the ranges acceptable to the Mark 3 VAL II controller. This requires a fast calculation of the robot kinematics, imposition of joint margins and avoidance of singularities. The controller features a Research Machines Nimbus VX-20 computer which contains a 80386 microprocessor with a 80387 floating point coprocessor.

Application Studies Decontamination and decommissioning are just two of many different applications which would benefit from the introduction of a nuclear engineered robot design. 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 NERO 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. Basic trials have shown the feasibility of deploying a hot spot decontamination head using a robot. [Figure 2].

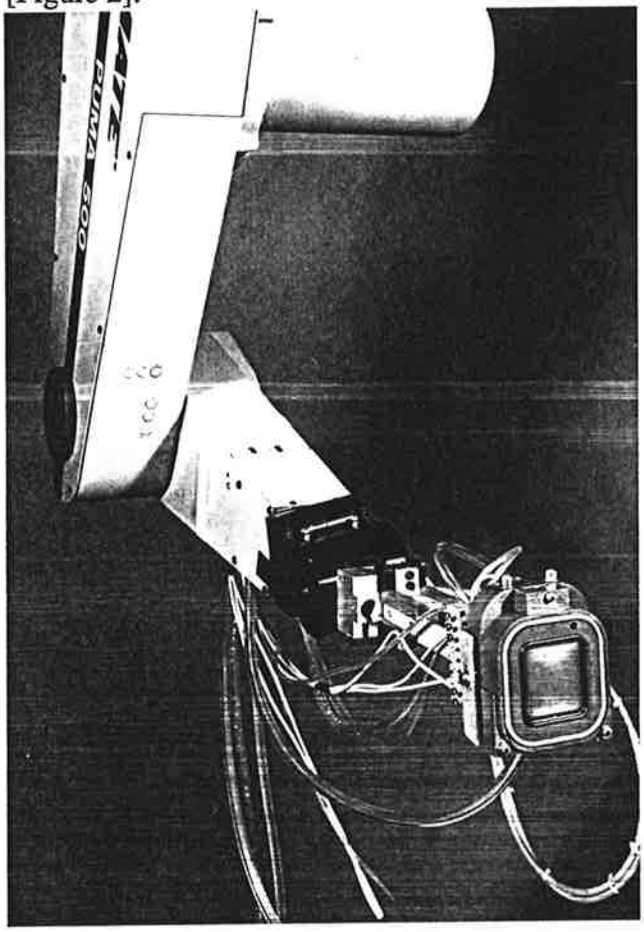

Figure 2. Non-Active Testing of Electro-Chemical Decontamination.

In addition, a simulation of a range of solutions was performed using GRASP, a robot kinematic and solid modeller, installed on an Apollo colour graphics workstation. 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. An example is shown in Figure 3. 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. A post-processor has been used to convert GRASP instructions to a VAL II off-line programme. The demonstration task consisted of generating an arbitrary planar raster scan of the end effector symptomatic of decontamination, or the cleaning of shielding windows, with a complient tool.

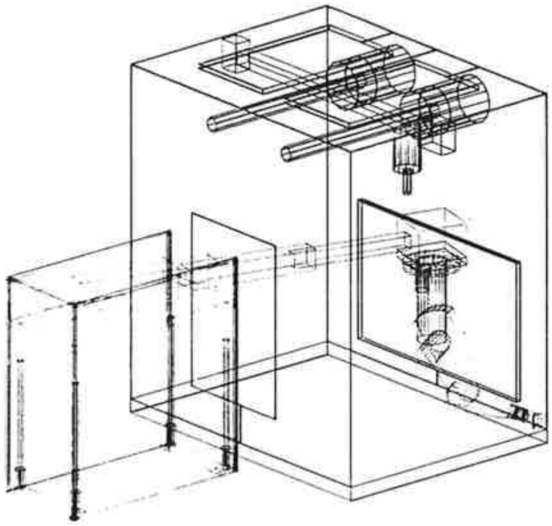

Figure 3. GRASP Simulation

12 A requirement to improve the effectiveness of pressurized suit workers involved in glovebox decommissioning has been examined, and a potential solution using a NERO and auxiliary remote handling equipment has been proposed. Simple proof-of-principle cutting trials have taken place, Figure 4, using easily available tools. GRASP has also been used to test the dynamic operation of the process of dismantling as well as the kinematic requirements of the remote handling devices. More specific trials are analysing the cutting, jig design, and retrieval of glovebox components, and tool changing techniques are being adapted from other in-house projects.

ROBOTICS DEMONSTRATION FACILITY

13 This facility consists of a demonstration area with a control room at each end. Figure 5 shows an inverted PUMA 560 robot suspended from an X-Y gantry system which can move the PUMA at speeds of up to $0.5 ms^{-1}$ in the 6x3x2m working volume.

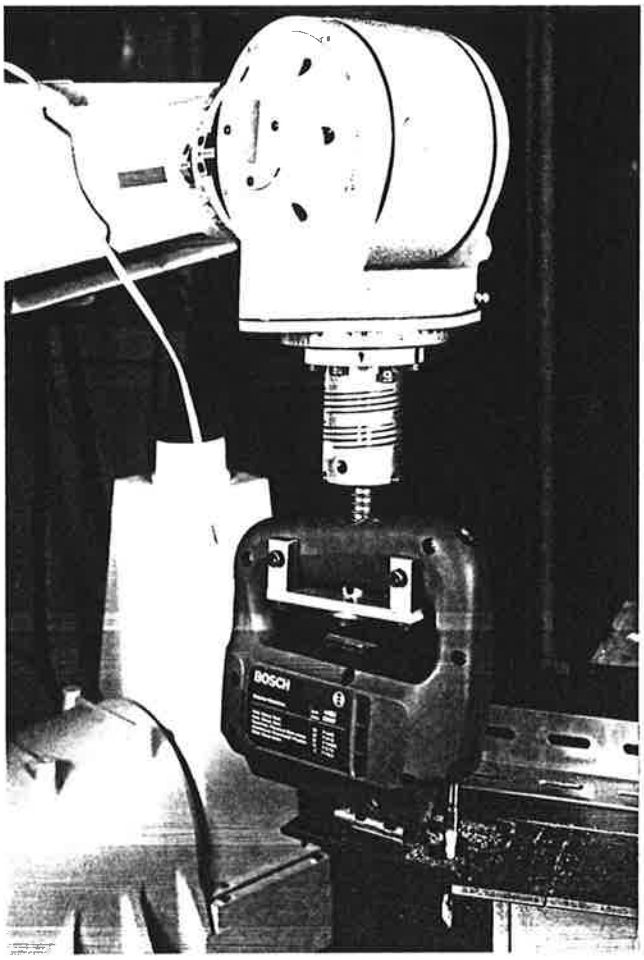

Figure 4. Elementary Cutting Trial under Teleoperation

In the working volume of the gantry is a floor mounted PUMA 761 robot. Above the gantry is a computer controlled 5 tonne crane 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 infra-structure, the hardware for realistic demonstrations of the principles of tele-operation 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.

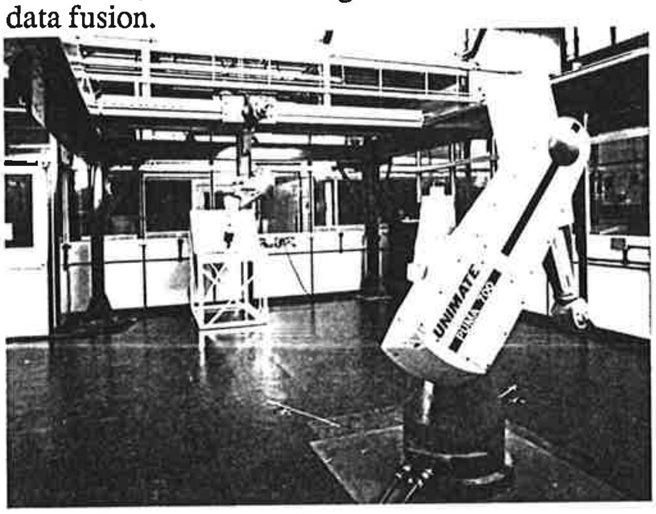

Figure 5. Robots in the RDF

Crane and Servo Control 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; the new long travel motor is shown in Figure 6. 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 retro-reflective elements. Despite the age of the crane and its original transmission elements, repeatable 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.

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

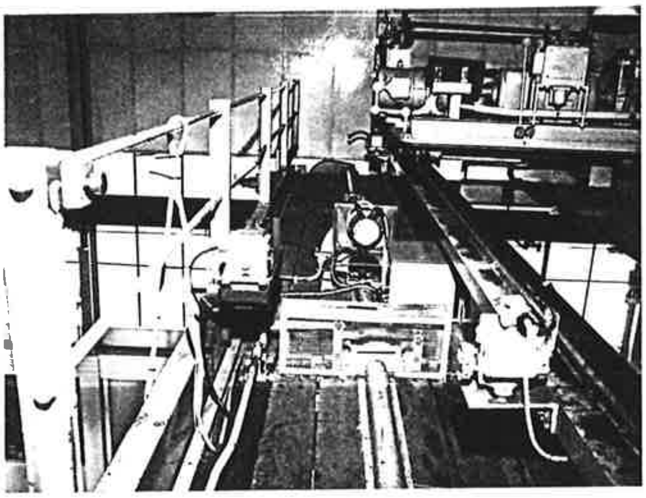

Figure 6. Crane Long Travel Motor & Shaft

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.

Several experimental manipulator powered joints have been produced with different torque ratings and gear ratios. The principle of an electronically back-driveable 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.[3]

Communications A broadband cable network has been installed to allow experimentation to take place into partitioning of systems for in and out of cell communications. The cable links the Robotics Demonstration Facility, the Indirect Viewing Laboratory, and a

Development Laboratory 400 metres away. The cable is routed through existing site underground heating distribution channels between buildings. A Headend rack accommodates signal processing equipment for video channels and remodulators/ frequency translators. Full band data channels as well as video are installed on the system. Signals are driven into the trunk network via a combining/launch amplifier. The distribution network amplifiers can drive four outlets, and each outlet drives cable splitters, directional couplers and cable taps, ultimately to the Network Access Points [NAPs]. A total of 24 NAPs are currently on the system, in the three laboratories. IBM PC-ATs or equivalents are used as system controllers and are linked on the broadband cable network. For example the communications between the joystick interface and the PUMA controller is via the network. Point to point video transmission over the network has been used to provide adequate viewing conditions for some of the teleoperation trials.

The Man-Machine Interface 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. Working in tool mode through our input device controller, both six degree of freedom input devices are easy to use and their characteristics can be quickly learnt. Correct alignment of axes relative to the operators' perception of tool or viewed tool coordinate systems is vital to effective teleoperation and is not necessarily intuitive. Low stiffness devices can suffer from gravity preloading which has to be compensated by the operator. Work has begun on developing a general purpose hand controller [Figure 7] which is based on the parallel kinematics of the Stewart platform.[5] The mechanism design is compact and easy to service and maintain. It has the potential to be a cheap and

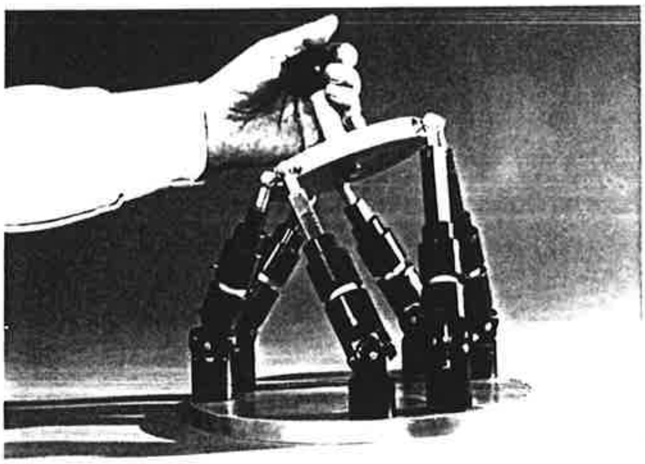

Figure 7. A Hand Controller Model Based on the Stewart Platform

versatile input device for teleoperation, and in its basic form can be used as a compound joystick.

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. The use of stereo with teleoperation without force feedback enables very specific and exact operations to be achieved, using the increased richness of the scene. In cutting demonstrations, [Figure 8] the use of the CAE hand controller, a colour stereo display and precise control over tool speed in all degrees of freedom allowed easy manipulation and alignment of the tool, minimising spurious contact forces, unexpected mis-alignments and unnecessary hesitation in repositioning the cutting blade for subsequent operations.

REMOTE INDEPENDENT SLAVE ARM

The Remote Independent Slave Arm [RISA] is a continued development of the Harwell hydraulic manipulator, with force feedback. Local and remote workstations will allow control of the slave arm using the single broadband cable communications network. Feedback of stereo vision,

Figure 8. Cutting Trials Using Stereo TV and a 6 Degree of Freedom Hand Controller.

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 or transporter. 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 described in Reference 3 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

The Harwell 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. The design of a nuclear engineered telerobot is nearing completion and the constructed prototype will be installed in an active area. Future work into remote workstation design, further systems integration and implementation will establish the ground rules for effective systems configurations based on truely remote handling.

ACKNOWLEDGEMENT

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