Nuclear telerobotics and 3-D TV – new tools for the industry

The remote handling and robotics group at Harwell Laboratory has, over the last five years, developed telerobotic techniques for use in the nuclear industry. The approach has been to apply available equipment, modify available equipment, or design and build anew. Ed Abel and Christopher Watson describe the developments.

The nuclear industry tends to be conservative in its approach to new remote handling technology. This is not surprising, since the penalties for the in-service failure of such equipment within an active environment can be very high, both as regards the cost of recovery and the risk or doses to operating staff in the process.

Consequently nuclear plant designers and operators tend to require full-scale, highly realistic inactive demonstrations of the reliability of any new technology on offer before they are prepared to incorporate it into active plant, or even into pre-construction pilot studies. They do not very often press for the development of new technology.

An active handling research group, such as the remote handling and robotics group at Harwell, is therefore obliged to operate at two levels – first to undertake generic R&D, aimed at developing equipment with new or enhanced capabilities, and then to customise this equipment to specific applications, and give convincing demonstrations of its effectiveness in those applications. Described below is new active handling technology which has been developed and demonstrated in this way at Harwell – in particular three systems:

- the nuclear engineered advanced telerobot (Neater);
- the hydraulic manipulator;
- the radiation-tolerant stereo TV.

These three developments, although initially undertaken within a generic R&D programme, have all advanced to the point where specific applications have been identified, and the corresponding inactive demonstrations have been successfully completed. The hydraulic manipulator is already experiencing active service; the other two systems will be introduced into highly active environments within the next few months.

R & D strategy

The Harwell R&D strategy in these areas has evolved over nearly a decade. At the beginning of this period, the emphasis was on innovation, and it was regarded as acceptable to design such equipment from scratch to meet each actual or anticipated requirement. Given the unusual nature of the requirements and the relatively primitive capabilities of industrial equipment available then there was little choice.

The hydraulic manipulator is a system which Harwell designed during this period. However during the last few years, it has become clear that innovation in the non-nuclear applications of remote handling, particularly in industrial robotics, has progressively outstripped that of the nuclear industry. Thus there has recently been a shift of emphasis at Harwell away from radically innovative design, and towards the adaptation of industrially available equipment to meet nuclear requirements.

These adaptations are by no means trivial – industrial products typically lack the radiation tolerance and easy decontaminability required by the nuclear industry, and they are normally better adapted to routine tasks in a highly structured environment than to the unpredictable tasks in disorderly environments which are liable to arise in nuclear applications. However it is still possible to benefit from the two primary advantages of industrially-manufactured equipment – its relatively high reliability and low cost.

An industrial robot, for example, is likely to have experienced many thousands of hours of trouble-free operation before it is launched onto the market, and the scale of production is such that the unit cost is many times lower than that of a one-off device specifically engineered for a given application. The challenge is therefore to retain these advantages, while at the same time meeting the nuclear requirements. The successful development of Neater shows that this is indeed possible.

Any remote handling system with a human operator in real-time control, for example Neater or the hydraulic manipulator, is only effective if the operator knows exactly what he is doing. The objective of the radiation tolerant stereo TV development programme was to ensure that the nuclear operator received as much visual information about his workplace, as if he were free to enter it and see for himself. Studies at Harwell have shown that the sense of depth provided by stereo TV is a vitally important part of this information, permitting the operator to undertake tasks quickly, and in the confidence that damage will not result to either the manipulator or the workpiece.

Although the main focus of the work at Harwell has been on teleoperation – ie operation of a robot or manipulator system with a man constantly in the loop, exercising real-time control – there are often circumstances (especially in such areas as decommissioning and waste management) where this constant operator control is exhausting, and ultimately unreliable. It therefore makes sense to move, as we have, towards semi-autonomous operation – ie to pass back to the machine those control tasks to which it is best suited, while leaving the operator in overall control. This approach, which has been called telerobotics, in effect combines the best of industrial robotics with all the skills of a human operator.

The teleoperation interface

To adapt an industrial robot for teleoperation, it is necessary to design some additional hardware and electronics to provide an interface between the human operator and the industrial robotic controller, which by itself can only effect pre-programmed sequences of operations. Some industrial controllers provide much more assistance than others to the designer of the interface. After surveying the available industrial controllers, particularly in relation to the facilities offered for on-line path modification, we selected the VAL II controller from Unimation, and we undertook some initial trials with a Puma 560 robot, using as the input device (master arm) a smaller, kinematically similar, serial linkage.

These trials confirmed that such a system was viable. However, it was relatively easy to trip out the robot controller by exceeding joint angle limits or by trying to drive through arm singularities. So instead of depending on the kinematics of the master arm, a microprocessor-based kinematic model

Figure 1. **The Harwell input controller**

of the arm was developed. Software within this microprocessor could then be used to condition demands from any of a range of possible input devices such as joysticks or forceballs, to ensure that limits and singularities were avoided. The operator could then drive the robot at full speed, in teleoperation mode, without compromising the robot performance. Since the microprocessor could also accept instructions to move from teleoperation mode to pre-programmed robotic mode, it could also act as a telerobotic controller.

The latest version of the Harwell input controller (figure 1) allows control of the robot in joint, world or tool co-ordinate systems. The operator selects the mode of operation of the input controller through a touch screen menu. Additional features include speed scaling, and constrained motion – where specified degrees of freedom can be suppressed or constrained – allowing straight line, planar motion or offset planar motion. These latest features give significant improvements in tasks such as scanning complex surfaces and drilling and cutting workpieces.

Nuclear engineering an industrial robot

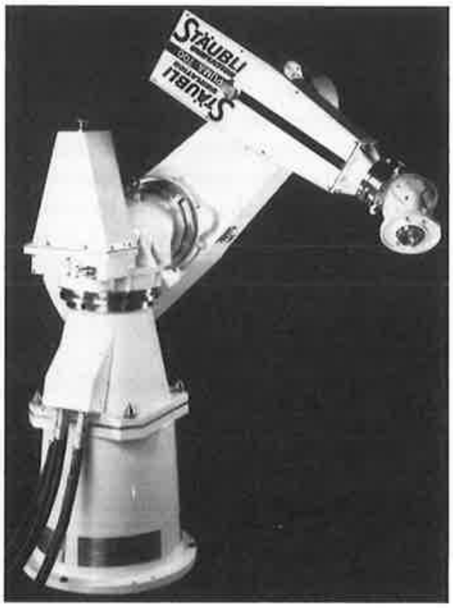
In selecting an industrial robot for adaptation to the nuclear environment, the primary requirements were the proven reliability of the robot, and the willingness of the manufacturer to engage in a joint development programme. This would involve considerable modification of the electrical and electronic components, the most vulnerable to radiation damage.

The robot had to have a reasonable load capacity and reach – say 20 kg at 1·5 m – and to have sufficiently protected working parts to make it decontaminable without excessive redesign. On all these grounds, the Staubli Unimation Puma 762 robot was selected. Its design has been thoroughly assessed, in association with the manufacturer, to ensure that all components are suitable for the most demanding nuclear environments. Improved seals at each joint and a wrist gaiter minimise the ingress of contamination.

The forearm can be easily removed to improve maintainability and a reduced base cuts down the weight of the arm. Wiring, connectors, bearings and other internal elements have also been examined and radiation tolerant alternatives have been produced where necessary.

The prototype Neater has been delivered to Harwell (figure 2). In all respects except one, the prototype is fully nuclear engineered, up to the design target of an integrated dose of 10^6 Gy before a major overhaul is required. The one exception is the set of six optical shaft encoders, used to sense the angle subtended at each joint. Design of (equally) radiation tolerant encoders is now well advanced, and these will be backfitted to the prototype shortly, thus completing the development programme.

Figure 2. **Neater – the nuclear engineered advanced telerobot**



Initial cost estimates for production models of Neater (the nuclear engineered robot plus an input controller) suggest that significant cost savings can be made

Figure 3. **The hydraulic manipulator**

compared to special purpose derived manipulators designed to a similar specification. In addition, Neater is based on a family of industrial robot designs which are operating successfully in many different countries.

The hydraulic manipulator

The Harwell hydraulic master slave manipulator (MSM)[3] is specially designed for through-wall use and can be used to directly replace existing MSMs (figure 3). Mechanically linked MSMs have reached their limitation in reach and load capacity, and are not particularly well suited to the production environments associated with reprocessing and waste handling. For those applications, loads can be substantial, and failures of conventional MSMs result in a loss of productivity and potentially high costs in maintenance, spares inventories and staff radiation exposures. The majority of conventional MSMs do not incorporate load balancing features and operator fatigue can be considerable.

The first machine built at Harwell was rated at 23 kg. Following successful trials at Sellafield, in a decontamination cell serving two magnox fuel element decanning caves[4], a second version of the hydraulic manipulator was designed with a load capacity of 30 kg at full reach (4·1 m) and a direct lift capability of 350 kg. The chosen fluid is water glycol operating at 210 bar; the manipulator is also controlled by a position difference servocontroller. A force-reflecting master arm is under development[5] to improve the performance of the manipulator, using a combination of control techniques. It will enhance dynamic performance and give the operator a sense of contact with the workpiece. A series of tests and simulations have been carried out to optimise the master joint actuators and a combination of direct drive, low transmission ratio and high gear ratio drives has been specified.

3-D TV

For effective teleoperation, visual feedback is as, if not more, important than force or position feedback from a manipulator. In particular, 3-D or stereoscopic TV enables operators to assess accurately the remote environment, for example, during inspection, or to interact remotely, accomplishing complex tasks involving manipulation or tool deployment. Studies began at Harwell in 1980 to verify the known potential of 3-D TV, by analysing the importance of the various controllable parameters which influence 3-D, building the best systems technically possible and measuring their performance in comparison to other TV systems[6-8].

These studies showed that 3-D TV gives the operator a perception of depth, scale, scene texture, and a confidence that a manipulative task can be completed in unfamiliar or cluttered environments. Other benefits are that often tasks can be completed more quickly using 3-D TV than with systems based on several 2-D TV arrangements, and sometimes new tasks that previously had been impossible can now be contemplated.

To engineer a 3-D TV system successfully requires attention to both display and cameras. The principle is to arrange simultaneous display of two pictures which are very accurately matched except for the small horizontal disparities which allow the perception of depth. It is as important to control the camera parameters as those in the display. The observer can accept scaling of images easily. Attempts to display scenes with excessive depth, or ones with vertical disparities or inconsistent matching of images result in discomfort and reluctance to use a system.

We have built several complete 3-D systems, black and white and colour,

Figure 4. **Colour 3-D camera**

and a radiation tolerant version (to an integrated dose of 10^4 Gy), which are easy to use and can be used comfortably over long periods of time. Initially we avoided using zoom lenses (which in radiation tolerant-forms are expensive and bulky) by constructing the camera-system using a turret lens change for wide and narrow angle views. The display technique is to use two good quality monitors, usually broadcast standard, modified for excellent picture matching, and a combining mirror. Camera pairs and monitors are optically matched to ensure that their alignments fall within the guideline values which we have set.

A colour system has been produced, (figure 4) which uses off-the-shelf camera sensors and a special lens mechanism. This mechanism, similar to that of the earlier black and white camera, controls focus and convergence simultaneously, to maintain coincidence of focal and convergence planes. The display (figure 5) is designed to be moved to a position alongside an existing workstation. A more compact display which can be built into a control desk has also been produced. The colour display can also be used as a 3-D computer graphics and simulation display. Techniques for the cost effective recording of 3-D TV pictures have also been developed[13].

Having gained experience in building experimental 3-D TV systems, and confirming their benefits and ease of use, a radiation tolerant version has been constructed, which is suitable for hot cells or reactor inspection. It is specified to operate at up to 150°C, it has its own lighting and it can be inserted through a 150 mm diameter tube.

Application-driven trials

All three systems described above were initially developed within a generic R&D programme – influenced, but not driven, by specific applications. In each case, a suitable nuclear application was then identified, and the system was customised to that application, and subjected to extensive inactive trials. These trials are discussed in the following sections.

Telerobotics applications

Two specific applications of telerobotics have been investigated. The first is the use of telerobotics to scan and monitor radioactive hot spots on a metal surface in a regular manner, and subsequently decontaminate the surface using an electrochemical method. This example makes use of a computer based kinematic model of the robot, its serving system and its target workplace, establishing compatibility of hardware and the

Figure 5. **Colour 3-D display**

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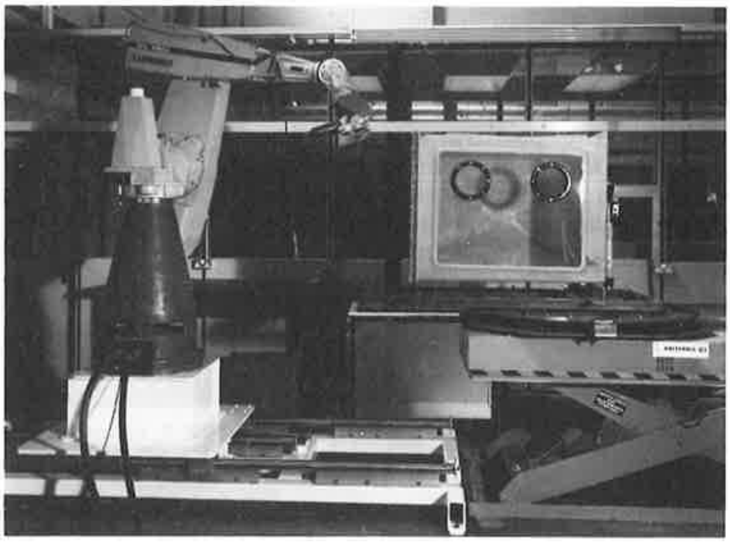
task[10]. A robot simulation package has been used to provide off-line programmes to control the robot when it is not operating under teleoperation. By using the Harwell input controller, particular degrees of freedom can be constrained to provide restricted motion, for example pure planar or pure linear motion. With feedback from position sensors, offsets and controlled compliant forces can be applied to an arbitrarily-oriented workpiece, which is necessary for effective deployment of the decontamination head.

The second application of telerobotics involves using slightly modified industrial cutting tools to effect size reduction of plant items such as gloveboxes. The telerobot deploys the tool under teleoperation (figure 6) and the glovebox can be reduced by nibbling, sawing, grinding or drilling. This task has hitherto been carried out by pressurised-suit workers, and a telerobotic solution can show a potential benefit in a longer cutting working day, reduced labour costs and less risk to personnel.

These tools, attached to the robot by a compliant tool mounting plate, work well. Tools with their own reaction forces and torques are preferable, to reduce wear in the robot transmission. If the task is not close to an operator, acoustic feedback can help him to determine the optimum tool feedrate under teleoperation. 3-D TV has also been used in this application, and with the addition of control software in the Harwell input controller, similar to that used in the decontamination application, tool feeds can be constrained to be parallel or normal to the glovebox surface even though the telerobot co-ordinate system is not aligned to the workpiece. A single six degree of freedom input device has been used to control the telerobot in tool or world co-ordinates, as we plan to extend our work to allow tool and interaction forces to be fed back to a force reflecting master input device.

Figure 6. **Glovebox size reduction**



In this use it is probably not cost-effective to automate the operation completely; it is better to leave some functions under operator control. For instance, as we currently envisage the task, the operator of the telerobot uses glove ports to change tools, replace broken blades and maintain end effector tooling. Figure 7 shows such an operation – changing a broken blade. The telerobot control is interlocked out before access to the glove ports is possible, and the telerobot and the tool just cannot reach the glove port wall.

Evaluation of viewing systems

Many evaluations of viewing systems have taken place in the viewing laboratory. Initially we undertook simple comparisons of performance between high definition and 3-D TV systems; these then gave way to more complex applications of TV involving some form of manipulator task. Comparisons have been made using force reflecting manipulators, a variety of task boxes and sorting tasks where depth information is important to avoid the uncertainty which is liable to arise in unstructured environments.

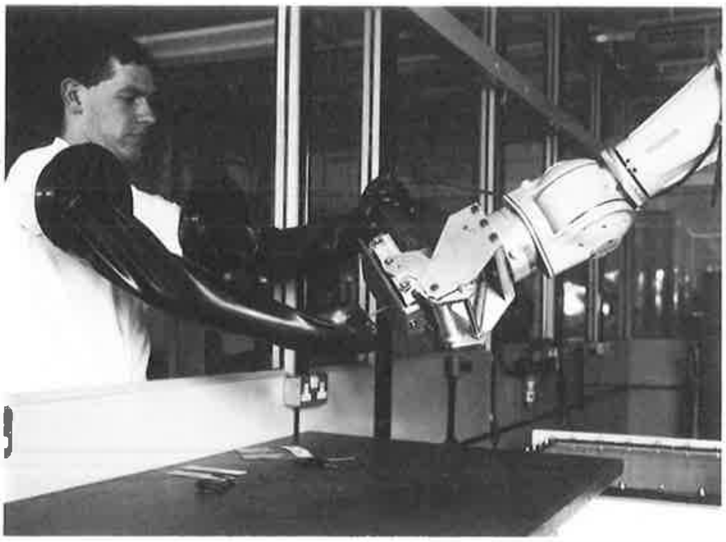


Figure 7. **Manual blade changing using gloveports**

Trials at Windscale Nuclear Laboratory have compared performance benefits of 3-D TV over two orthogonal 2-D TVs, in operations such as remotely cropping reinforcing bar using an industrial robot carrying a hydraulic tool[8].

Another experiment, also at Windscale, evaluated the benefit of a colour 3-D TV system in a decommissioning operation which involved handling large steel plates, representing samples of cut reactor pressure vessel. The plates had to be grabbed by a crane and located precisely in a rack prior to cementation[11].

A visual perception experiment has investigated the effect of flicker rates on visual search tasks for different frame rate displays[12]. Some guidelines for reducing flicker in control rooms have been set, and work in this area continues. We have identified flicker as a major problem in the acceptability of some commercially-available 3-D TV systems for long-term use.

Lessons learned

Telerobotics using industrial robots has required the development of a special microprocessor-based input controller. The benefit is that the attributes of the robot controller and the robot performance are not degraded by teleoperation. The input controller can work with a variety of input devices, allows a selection of control modes such as tool alignment, predeterminate degrees of freedom, tool offset or compliance, scaled tip speed and can act as a conditioning unit for sensor information used to actively control the telerobot trajectory. Six-degree-of-freedom hand controllers are available which can be used to control the robot at low cost, and are simple to operate.

Re-engineering a robot for the nuclear environment is not a trivial task. However, by careful analysis of the materials and construction, radiation tolerance can be built into a design which differs only slightly from industrial production machines. To accomplish re-engineering requires a good working relationship with the robot manufacturer, to ensure a thorough understanding of the initial design principles and the manufacturing techniques involved.

For the hydraulic manipulator trials at Sellafield have confirmed the soundness of the basic design of the prototype machine. In the early months we experienced a number of minor failures; their remedy has led to the development of an improved machine. The new machine has a stronger wrist, a greater load capacity, and can be installed from the cold face with a gaiter already fitted. It will fit into a 254 mm MSM port, and has extended reach. As it stands, the basic manipulator has two alternative operator input mechanisms – a kinematically similar master arm or a simple box containing potentiometers for position demands. However a force reflecting master arm is now under development.

The trials highlighted the need for post-repair pre-installation tests, and training courses for maintenance and operational staff. A shrink-fit sheath on the original arm has been shown to be effective in reducing contamination traps and results in acceptable levels for contact maintenance following simple swabbing. The jaw assemblies have been decontaminated using a caustic bath, and a jaw change station has been constructed to permit the automatic replacement of damaged end effectors.

The manufacture of 3-D TV displays and cameras has confirmed that the demanding design performance can be achieved by careful attention to detail. Although 3-D TV does not in every case show significant benefit in the time for a simple operation, it is of quantifiable benefit in many typical remote handling tasks which require complex decision-making processes, relating to an operator's perception of unfamiliar or ill-ordered scenes.

If the task requires ballistic motions of a high quality manipulator in cluttered or restricted workspaces, the 3-D TV shows a significant improvement in performance of the task compared to single 2-D TV or combinations of cameras. 3-D TV is not as critically dependent on position or deployment throughout a task and is not so badly affected by lighting variations.

For any task that requires judgements to be made about surface texture (eg during inspection) or about the interactions of a manipulator, 3-D TV shows tangible and significant benefits compared to other TV techniques. In our view, the budget allocated to TV systems in a remote handling system should at least be on par with that allocated to the manipulator system itself. We also believe that assessments of TV systems which include observation of the operator, give a better insight into performance than do the classical analyses of task and subtask completion times. In particular, indicators of operator fatigue, and strategies for task completion can be identified by analysis of the experimental video record.

Caution

The understandable caution of the nuclear industry in accepting new remote handling technology makes it necessary to undertake generic R&D to develop such new technology, and then to follow up these developments with inactive trials of the new systems, customised to specific practical applications. This approach has been followed for three new systems – a nuclear engineered robot, a hydraulic manipulator, and a stereo TV system. In each case the trials have shown that these new tools are now ready for exploitation by the nuclear industry. ■

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