TELEROBOTICS AND 3-D TV - - WHAT YOU NEED TO KNOW

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Abstract

Work at Harwell Laboratory over the last five years has concentrated on developing telerobotic techniques that can be used in the nuclear industry. The approach has been to apply available equipment, modify available equipment, or design and build anew. We have successfully built an input controller which can be used with standard industrial robots, converting them into telerobots. A clean room industrial robot has been re-engineered into an advanced telerobot engineered for the nuclear industry, using a knowledge of radiation tolerance design principles and collaboration with the manufacturer. A powerful hydraulic manipulator has been built to respond to a need for more heavy duty devices for in-cell handling. A variety of easy to use 3-D TV systems has been developed to enable versatile totally remote teleoperated systems to become viable options for the nuclear industry. Each of these examples required careful attention to be paid to design criteria, performance evaluation, application studies, trials and human interaction. The philosophy that has been used in their development is presented, together with a description of the resultant hardware.

1. INTRODUCTION

Nuclear remote handling is an ideal field for conservatism. New plant design is always constrained by the available [and proven] techniques demonstrated in existing plants. Plant designers and operators need sufficient and substantial proof of new techniques before they can be incorporated into active plant proposals or even into pre-construction pilot studies. Research groups, in comparison, tend to develop equipment which may not address operational needs, and which can be difficult to operate economically in real applications. In principle, both groups should be able to realize common objectives, develop new equipment to advance plant design and produce innovation which refreshes the possibilities of achieving more complex tasks in remote handling more effectively.

Traditionally, research and development at Harwell Laboratory focused either on producing specialized equipment to well defined project requirements, or on long-term objectives. Although this had advantages, the carry-over of innovation from project to project was minimal, especially in the case of control system design. In 1984 the prospect of continually evolving new and unique solutions to remote handling with little benefit accruing from previous projects was not attractive. At the same time, it was appreciated that innovation in the non-nuclear application of mechanical handling, especially in industrial robotics, had begun to outstrip progress in the nuclear industry. An extensive assessment of technology that is needed for computer-aided remote handling indicated that many of the techniques used in automation could be readily transferred to nuclear applications, provided cognizance was taken of the special requirements of the environment and difficulties associated with remote maintenance.[1] For historic reasons, the UK had not developed a commercially available electrically linked master slave manipulator, and so the concept of producing a new type of remote manipulator was considered. The new manipulator could be

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based on a commercially available industrial robot with the addition of a teleoperation interface and environmental re-engineering. In parallel with this reasoning, a heavy duty special purpose hydraulic manipulator was being developed, as an upgrade to existing master slave manipulators. 3-D TV systems were designed to ensure that comfortable and easy to use remote viewing technology was available for inspection of maintenance tasks, complementing the improved potential of remote manipulation.

The three developments, of re-engineering an industrial robot, building 3-D TV systems and producing a hydraulic manipulator represent combinations of the three basic routes to producing effective nuclear remote handling equipment. The three routes are:

- apply available equipment
- modify available equipment
- design and build anew.

This paper describes how our recent developments incorporate blends of adaption and special design, and indicates the value that can be gained by performance evaluation studies to refine hardware designs or philosophy of application.

II. TELEROBOTICS

Nuclear remote handling has evolved the concept of adjacent handling, where typically an operator views his work through a shielding window and uses a pair of mechanically-linked master-slave manipulators [MSM]. Because of the mechanical link the operator must be located at the cell face, Figure 1, and often for processes which require many working positions, the manipulators and windows are significant factors in initial [capital] and lifetime [maintenance] costs. For tasks such as waste receipt, posting operations, inspection and monitoring, as well as decommissioning, the use of fixed envelope manipulators may not be appropriate, and wall or mast-mounted manipulators provide improved volume coverage. A selection of electrically linked force feedback manipulators are available worldwide, but their cost and perceived reliability have prevented their widespread adoption, even though their development has been over a 30 year period.

Figure 1 - Hot Lab Operating Face

Distillation of the essence of a remote handing system reveals only three major constituents. These are:

- an end effector that can be positioned and oriented at a distance
- transmission media for power and control
- a human operator with an objective.

Using an industrial robot with a human operator in real-time control will realize all three constituents of remote handling. Topographical constraints mean that such a solution is not a panacea for all applications, but there are a significant number, especially in decommissioning and waste management, where human operated robots can be applied. The concept of using a robot with a human operator rather than a predetermined programme managing trajectory control is commonly known as telerobotics. Telerobotics defies exact definition, but we describe it as a combination of all that is best in industrial robotics with all the skills of a human operator to respond to ill defined and unpredictable tasks.

To achieve telerobotic operation in a nuclear environment requires the development of a teleoperation interface to a robot controller and the modification of a robot to suit the radiation environment in a reliable and maintainable form[2].

The Teleoperation Interface

A review of industrial robots highlighted the variable performance of the control systems.

Some manufacturers offered on-line path modification and the potential for telerobotic operation. The VAL II controller from Unimation was selected as being a suitable benchmark and initial trials using a scaled-down model master arm with similar kinematics, confirmed the potential of such an approach. However, it was relatively easy to trip out the robot controller by exceeding joint angle limits or by trying to drive through arm singularities. A microprocessor based kinematic model of the arm was derived and used to condition demands from input devices such as joysticks or forceballs. The operator can then drive the robot at full speed, as a telerobot, without compromising the robot performance, or loosing the ability to execute programmed operation. The latest version of the Harwell Input Controller [Figure 2] 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 [Figure 3]. Additional features include speed scaling, and constrained motion - where specified degrees of freedom can be supressed 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.

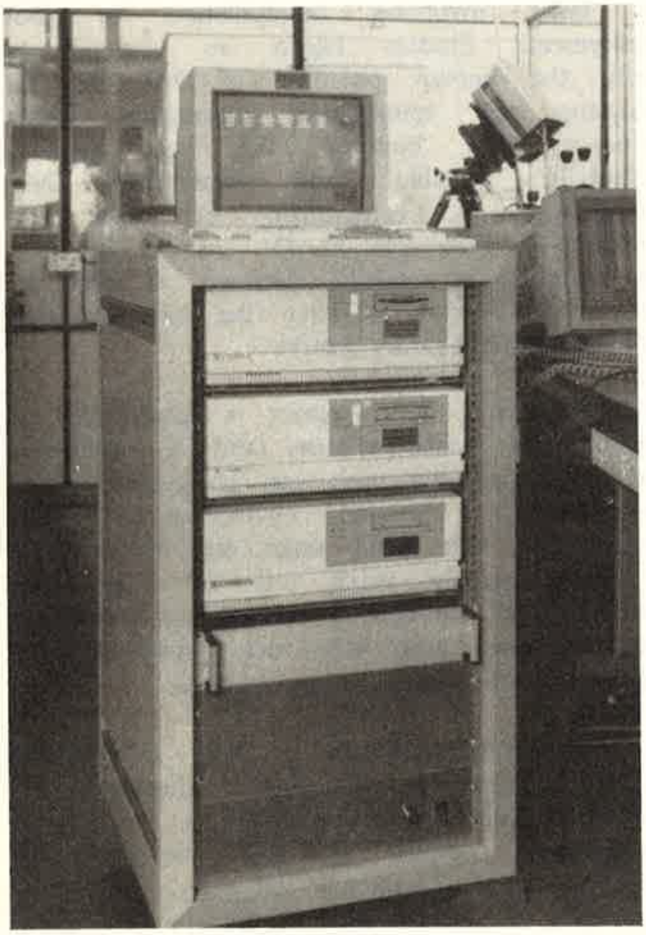

Figure 2 - The Harwell Input Controller

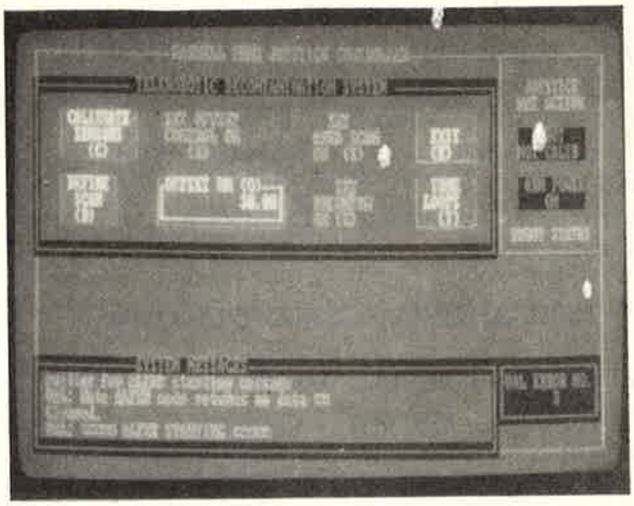

Figure 3 - A menu for the Harwell Input Controller

Nuclear Engineering an Industrial Robot

One of the major benefits of adapting an industrial robot to a nuclear environment is that any weaknesses in the mechanical design have been discovered by the operation of hundreds of units. The Stäubli Unimation PUMA robot was selected as the ideal manipulator for nuclear engineering. The design modification is based on a clean room PUMA 762 robot which has a full speed payload of 20kg. The arm 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 minimize 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 Nuclear Engineered Advanced Telerobot [NEATER] was delivered to Harwell in December 1989, and the concluding back fitting of improved performance components has been completed. The design target is for an integrated dose level of 10^6 Gy before the need for a major overhaul occurs, and samples of all components have been individually tested to beyond this level.

Initial cost estimates for production models of NEATER [the nuclear engineered robot and a input controller] suggest significant cost savings can be made 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.

III. THE HYDRAULIC MANIPULATOR

The Harwell Hydraulic Master Slave Manipulator[3] is a specially designed manipulator that can be used to directly replace existing MSMs. Mechanically linked MSMs have reached their limitation in reach, and load capacity and are not particularly well suited to the production environments associated with re-processing and waste handling. For those applications, loads are substantial and MSM failures result in a loss in productivity and potentially high costs in maintenance, spares inventories and staff radiation exposures. The majority of MSMs do not incorporate load balancing features and operator fatigue can be considerable.

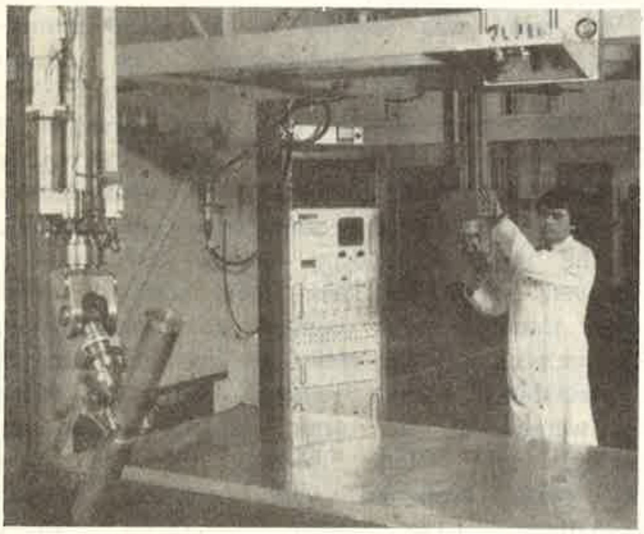

Figure 4 - The Hydraulic Manipulator

The first Hydraulic Manipulator built [Fig.4] was rated at 23kg. Following successful trials at Sellafield, the second version of the machine was designed for a load capacity of 35kg with a direct lift capability of 350 kg. The chosen fluid is water glycol operating at 210 bar and the manipulator is also controlled by a position difference servo-controller. A force reflecting master arm is under development[4] 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 optimize the master joint actuators and a combination of direct drive, low transmission ratio and high gear ratio drives have been specified.

IV. 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 accurately assess the remote environment, for example, during inspection, or to interact remotely, accomplishing complex tasks involving manipulation or tool deployment. Studies began at Harwell to verify the known potential of 3-D TV, by analysing the controllable parameters which influence 3-D, building the best systems technically possible, and measuring their performance in comparison to other TV systems[5-7]. The use of TV systems in remote handling is usually confined to observation; direct viewing is often the medium used for manipulator or gantry control.

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 successfully engineer a 3-D TV system requires attention to both display and cameras. Because the principle is to arrange simultaneous display of two pictures with only a slight horizontal disparity, 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 resistance to use a system. We have built several complete 3-D systems, black and white and colour, and a radiation tolerant version, which are easy to use and can be used comfortably over long periods of time. An early camera [Fig 5] avoided using zoom lenses [which in radiation tolerant forms are expensive and bulky] by being constructed from four split-head cameras, each with their own lenses. The cameras form two pairs, one with wide angle lenses, one with narrow angle lenses [replacing the function of a zoom] and the display technique is to use two good quality monitors and a combining mirror. Camera pairs and monitors are optically matched to ensure their alignments fall within our guideline values.

Figure 5 - Black and White Twin 3-D Camera with Wide and Narrow Angle Lenses

A colour system has been produced, [Fig 6] which uses off the shelf cameras and a special lens mechanism. This mechanism, similar to those in Fig 5 controls focus and convergence simultaneously, to maintain coincidence of focal and convergence planes.

The display [Fig 7] 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 been produced. The colour display has been used as a 3-D computer graphics and simulation display.

Having gained experience in building experimental 3D-TV systems, and confirming their benefits and ease of use, a radiation tolerant version has been constructed. Its specification calls for operation at 150°C; it must have its own lighting and be no more than 150mm in diameter. Fig 8 shows the complete camera, which is suitable for hot cells or reactor inspection.

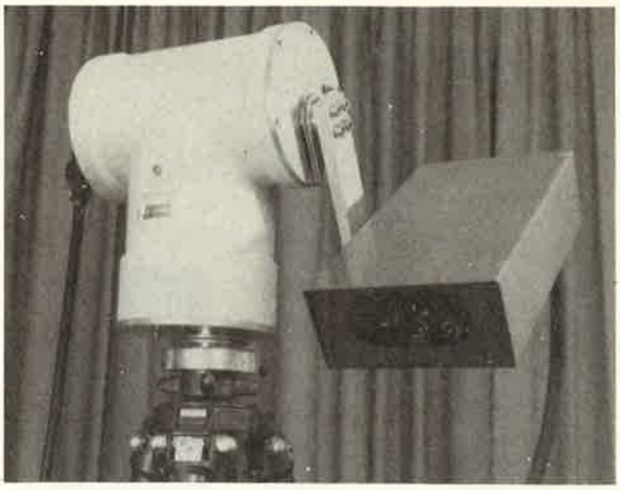

Figure 6 - Colour 3-D Camera

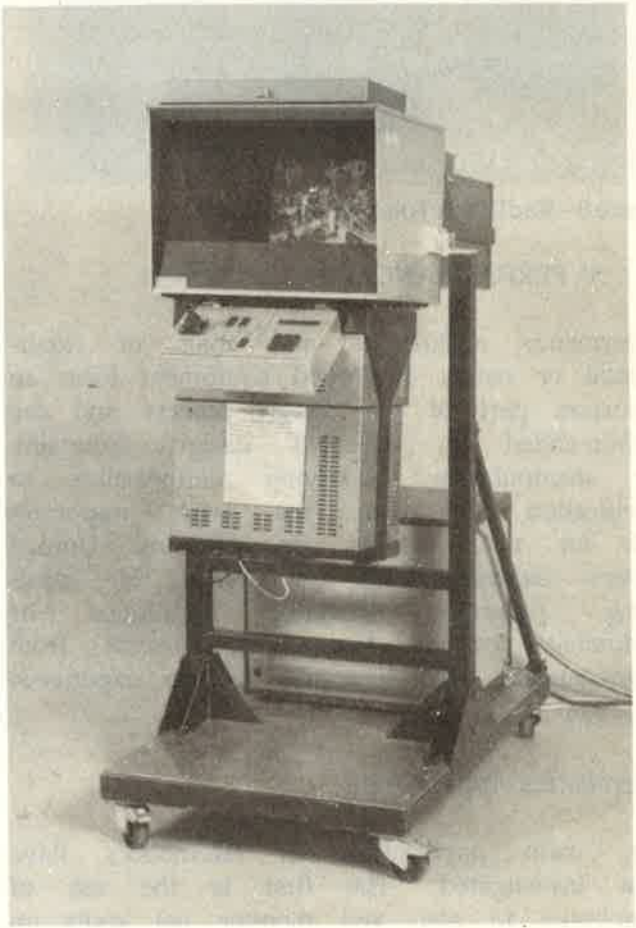

Figure 7 - 3-D Colour Display

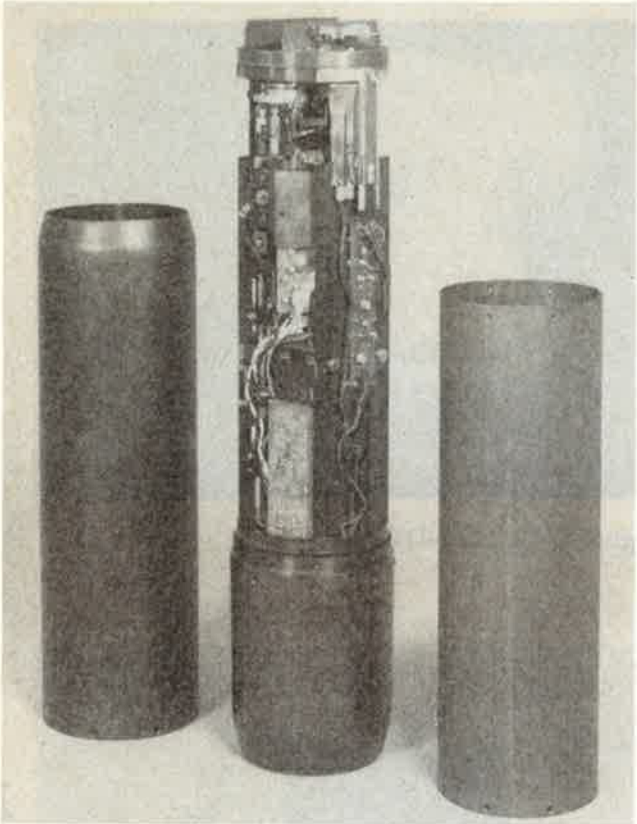

Figure 8 - Radiation Tolerant 3-D Camera

V. PERFORMANCE EVALUATIONS

Performance evaluations and trials of experimental or newly developed equipment form an important part of the design process and are recommended in accepted design criteria[8]. For manipulators, qualifying performance to specification is often the most important task for new models. In addition, Human Factors experimentation is useful in identifying particular working techniques or equipment features that could benefit from improvement. Some examples of our experience are given.

Telerobotics Applications

Two main applications of telerobotics have been investigated. The first is the use of telerobotics to scan and monitor hot spots on a surface in a regular manner, and to successively 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 task[9]. The simulation system has been used to provide off-line programmes for the robot when 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 tools to achieve size reduction of plant items such as gloveboxes. The telerobot deploys the tool under teleoperation [Fig 9] and the glovebox can be reduced by nibbling, sawing, grinding or drilling. This task is currently carried out by pressurized-suit workers, and a telerobotic solution can show a potential benefit in a longer cutting working day and less risk to personnel.

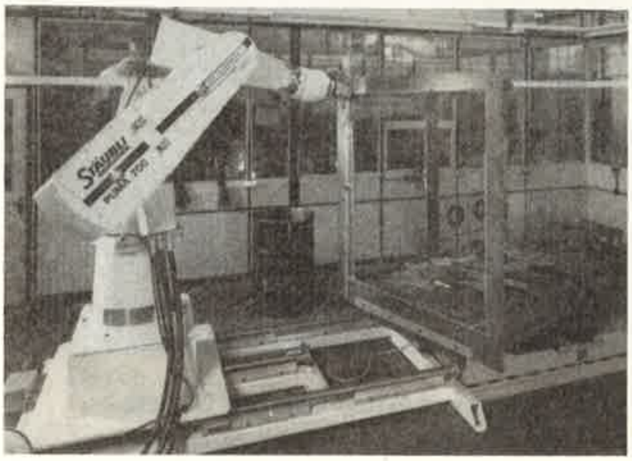

Figure 9 - Glovebox Size Reduction Trial with NEATER

The use of available tools with compliant tool mounting plates works well. Tools which contain reaction forces and torques are preferable, to reduce wear in the robot transmission. If the task is not close to an operator, acoustic feedback is helpful to determine tool feedrates under teleoperation. 3-D TV has been used in this application, and with the addition of control software in the Harwell Input Controller similar to the decontamination application, tool feeds can be constrained to be parallel or normal to the glovebox surface even though the telerobot co-ordinate sytem 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 coordinates, and we will extend our work to allow tool and interaction forces to be fed back to a force reflecting master input device.

The target application is envisaged as only semi-automated. To achieve a completely reliable tool package which will not need resetting or replacement, and to develop a tool change station is not considered necessary, in this instance. Instead, the operator of the telerobot will be able to use glove ports to change tools, replace broken blades and maintain end effector tooling. Figure 10 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 tool just cannot reach the glove port wall.

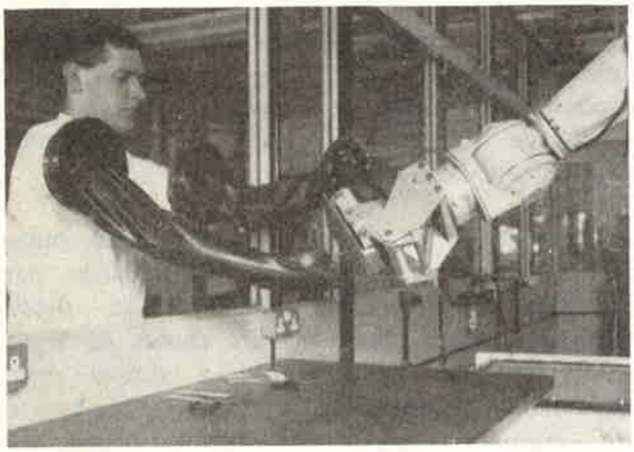

Fig 10 Manual Blade Changing Using Gloveports

Operating Experience of the Hydraulic Manipulator

Active trials lasting over 3 years have taken place at a decontamination cell serving two Magnox fuel element decanning caves[10]. The purpose of the trial was to replace an existing MSM and demonstrate performance and maintainability benefits of the hydraulic manipulator compared to continuing with the existing MSM. Using the first Hydraulic Manipulator from Harwell, which had undergone rigorous endurance trials, the cell equipment, such as slitter heads, sludge pumps, MSM extension pieces and lengths of plastic, was usefully manipulated and broken down.

The trials demonstrated that the hydraulic manipulator was eminently suited to cave work where typical loads are well in excess of the existing MSMs' capacity. Modifications to the design to improve strength, add versatility, and facilitate maintenance and decontamination were tried out and a new manipulator was built incorporating the knowledge acquired at the trial.

Evaluation of Viewing Systems

Many evaluations of viewing systems have taken place in the Viewing Laboratory Fig 11.

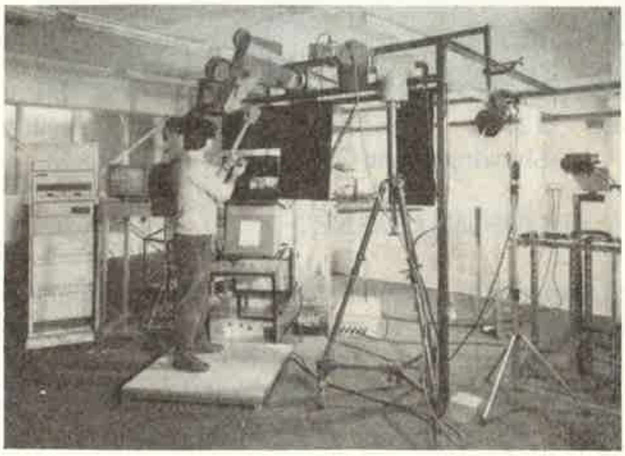

Figure 11 - Assessment of TV Performance

Initially, simple comparisons of performance between high definition and 3-D TV systems 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 uncertainty in unstructured environments. Trials at Windscale Nuclear Laboratory have compared performance benefits of 3-D TV over orthogonal TV in operations such as remotely cropping reinforcing bar using an industrial robot carrying a hydraulic tool[7]. 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 [Figure 12][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.

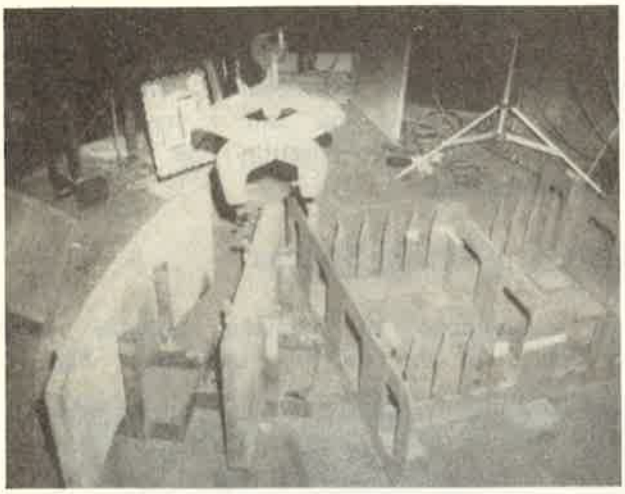

Figure 12 - Windscale Evaluation Facility Showing Crane Grab and Mounting Rack

VI. LESSONS LEARNED

Our experience gained during the evaluations and trials covers a variety of effects. Human factors experiments associated with the trials give insight into the subtle effects of operator performance and sensitivity to ineffective equipment.

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 take a choice 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 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, active trials have confirmed the performance of the prototype machine, and the experience of failures and their remedy has led to an improved machine being produced. 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 254mm MSM port, and has an extended reach. The basic manipulator is not force reflecting. Two input devices are available for position demands: a kinematically similar master arm, and a cheaper small control box which contains potentiometers to drive individual axes. 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 was effective in reducing contamination traps and resulted in acceptable levels for contact maintenance following simple swabbing. The jaw assemblies were decontaminated using a caustic bath, and a jaw change station was used to automatically replace damaged end effectors.

The manufacture of 3-D TV displays and cameras has confirmed the design guidelines can be achieved by careful attention to detail. Although in some cases 3-D TV shows no significant benefit in the time of a simple operation, many typical remote handling tasks require complex decision making processes relating to an operator's perception of unfamiliar or ill-ordered scenes. If the quality of manipulation is good, and the task requires ballistic motions in cluttered or restricted workspaces, then 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. In short, for any task that requires judgements to be made about surface texture [inspection] or interaction of a manipulator, 3-D TV shows tangible and significant benefits compared to other TV techniques. The budget allocated to TV systems in a remote handling systems should at least be on par with the manipulator system. Experiments 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, operator fatigue, and strategies for task completion can be identified as the experimental video record is analysed.

VII. CONCLUSIONS

Non-active trials are necessary to confirm performance and strategy of operation, and computer simulation helps avoid uncertainty. Human Factors assessments of the trials allow an insight to be gained into the subtle effects of operator performance and sensitivity to ineffective equipment. Specialized equipment is necessary for existing and future plants, but significantly our work has indicated that there is a very strong rôle for modified equipment to be brought into the nuclear marketplace. 3-D TV has become a useful tool and with NEATER, promises to be a cost effective alternative satisfying the need for new adjacent and remote handling techniques.

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