Advanced robotics and remote handling

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In the past decade, the industrial robot has at last reached commercial maturity. Robotics technology is poised for a significant change in complexity, with the advent of the advanced robot, a computationally intense, sensor-driven manipulator which operates with a high degree of autonomy. Nuclear engineers have seen the benefits of using such devices — increased safety, reduced costs, dose savings, and operational flexibility. A tremendous range of applications, from simple health physics surveillance to reactor inspection and repair, are rapidly becoming the province of the advanced nuclear robot.

Remote handling of nuclear and irradiated materials throughout the fuel cycle is well established. Conventional technologies have been used to ensure reliable and predictable operation. The special environmental constraints on equipment design tend to produce hardware that has not found a market outside of the nuclear industry. Conversely, non-nuclear industry designs of manipulators have proved difficult to adapt and have rarely been cheaper than purpose-built systems.

In recent years, several factors have influenced a dramatic turn-around in the philosophy of remote handling equipment design. Increasingly stringent safety requirements calling for reduced radiation exposures have put the pressure on the equipment designer. Rapid technology advances in computing, control, and microelectronics, coupled to a comprehensive theoretical understanding of manipulator kinematics and dynamics, have meant that it is possible to design and manufacture complex and compact mechanisms, with an assured performance specification. With a worldwide installed base of more than 100 000 robotic systems, throughout all the major industrialised countries, applications experience abounds, and can be exploited by adopting similar solutions to nuclear remote handling problems.

Applications for nuclear advanced robotics include fuel fabrication, health physics surveillance, decontamination, reactor inspection and repair, refuelling, hot cell manipulation, remote maintenance, posting and transfer, reprocessing, waste drum processing, decommissioning, and flask and pipework inspection.

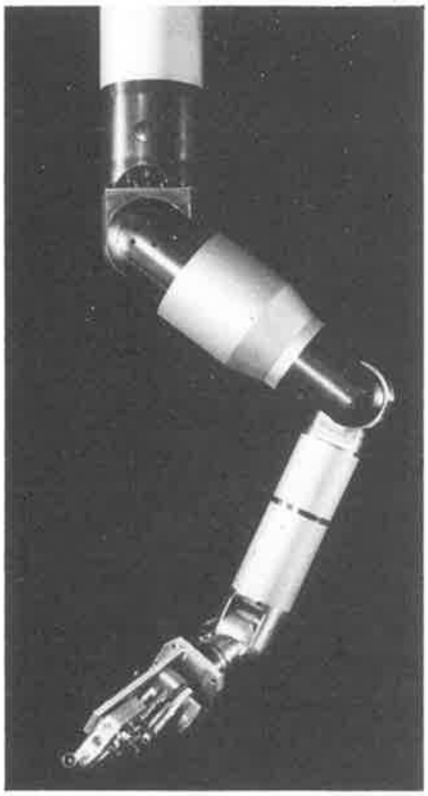
Radiation damage to robotic subsystems is the only major hurdle preventing widespread applications of advanced robotics (AR) to nuclear facilities and the only substantial factor which sets the nuclear advanced robot apart from non-nuclear applications. The extent of any redesign for radiation tolerance depends on the task that has to be performed. Simple health physics surveys carried out by remotely controlled (or autonomous) vehicles are unlikely to need any special attention, and would use commercially available systems.

As the integrated dose seen by equipment increases, shielding or redesign will be needed for critical items such as electronics, optical systems (including CCTV), and perhaps even structural materials. For extreme applications such as fuel reprocessing or inspection and repair of light water reactor primary circuit components, virtually all electronics and computing hardware will be some distance from the manipulator. Unfortunately, every major advance in semiconductor fabrication technique and increase in packing density invariably reduces the radiation tolerance of devices by roughly an order of magnitude.

Terminology

Robotics has its own terminology. A *teleoperator* is simply a manipulator which is controlled from a distance, in real time, by a human operator. Hot cell mechanically linked master-slave manipulators are teleoperators, and so is the space shuttle manipulator. A *servo-manipulator* uses servo-actuators to move joints (rather than a direct mechanical linkage to a master arm) and the actuators are usually electrically controlled. *Bilateral servo-manipulators* are invariably configured as master-slave pairs, with an electrical link. *Robotic manipulators* can be programmed to perform repetitive, pre-determined tasks. An *advanced robot* is a teleoperator that displays the attribute of both a robot and a servo-manipulator, depending on the mode of operation selected by the operator.

Servo-manipulators are used today to

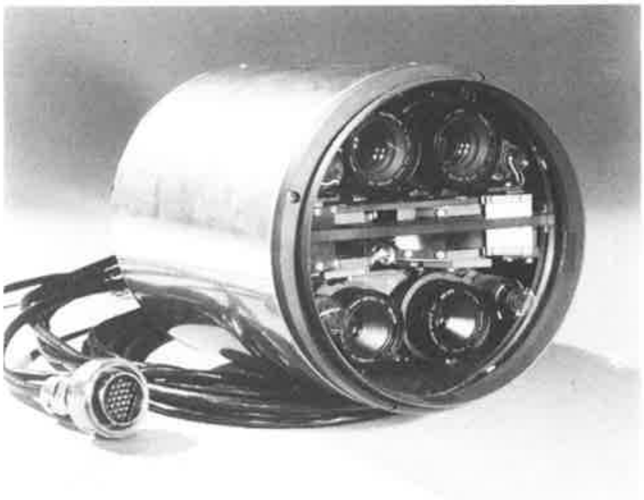


Warrior, a gas-cooler reactor repair servomanipulator.

inspect and repair power reactors. In the UK the Central Electricity Generating Board has developed a variety of long slender manipulators for use in magnox and advanced gas cooled reactors, where access is limited to the narrow-diameter standpipes above the core. The servo-manipulators can deploy sensors and cameras for inspection, and complex tool packages for specific repair operations involving cutting, drilling, bolting, and welding.

Warrior, the latest in a series of servo-manipulators with six degrees of freedom, uses precision gearing and state-of-the-art motor drives to achieve high-quality MIG welds in a magnox reactor. For light water reactors, steam generator tube inspection and repair is necessary; Westinghouse's Rosa is introduced into the channel head through the manway and locates itself on the tube sheet. Both types of machine effectively reduce the plant downtime, increase the quality of repair and the reactor life, and

Scobotman, a heavy duty servomanipultor.



A practical stereoscopic TV camera.

significantly reduce the man-dose accumulated during inspection and repair operations.

For the heavy duty servo-manipulators that will be encountered in decommissioning or waste drum handling, remotely operated cranes or machines such as the Lamberton Robotics Scobotman can be used, with varying degrees of radiation hardening. Both systems rely on man-in-the-loop operation, but could be easily arranged for totally remote programmed tasks.

Before robotic technology existed, electrically linked master-slave manipulators were developed in the USA, Italy, Germany, and France. An operator moved a master arm in the same way as he would move a conventional through-the-wall master-slave manipulator, and the motion was similarly replicated at the remote slave unit. The control system was designed to produce the sensation of force reflection as well as position matching at the master arm, to give the operator a sense of feel. Because this reflection of force and position was apparent in both directions, these servo-manipulators were known as bilateral.

In the mid 1960s the apparent added complexity of the systems prevented more than a handful of active-duty machines from being produced. Nevertheless, the designs matured and were uprated to reflect developments in technology. Current prototype systems are configured to allow left and right handed pairs of manipulators to be mounted together, with gross positioning achieved by a telescopic mast, a powered-boom linkage, or simply a counterbalancing package slung from a gantry crane.

Advanced servo-manipulators have many of the attributes of advanced robots, such as hybrid force/position control, adaptive compliance, computer controlled teleoperation, programmed tool changing, voice input control, and image-based trajectory control. Contamination control and ease of decontamination and maintenance are addressed in the designs to reduce the dose accumulated during maintenance.

As well as nuclear-oriented applications of servo-manipulators, several national programmes have been defined to extend the use of the technology to non-nuclear applications. This in turn assists the nuclear programmes. In France in 1975 a project called Spartacus aimed to develop a servo-manipulator for tetraplegics. The experience gained from that work was incorporated into the national automation and advanced robotics (ARA) programme, and CEA focused on the idea of computer-aided teleoperation using the MA23M bilateral servo-manipulator. With other topics such as AR, mechanics, and flexible manufacturing systems, ARA involved up to 160 full-time researchers and 30 industrialists. Government and public funding has amounted to about $70 million on research and development.

In the USA, major advances in servo-manipulator deployment have most recently occurred at Oak Ridge National Laboratory (ORNL), under US Department of Energy funding, as part of the consolidated fuel reprocessing programme. These major test facilities, based on full-size mock-ups of remote maintenance concepts, have provided a wealth of design and human factors results through realistic demonstrations of bilateral servo-manipulator capabilities. Two were equipped with modified and updated servo-manipulators — the M2 from Sargent Industries Central Research Laboratory and the SM229 from the Teleoperator Systems Inc.

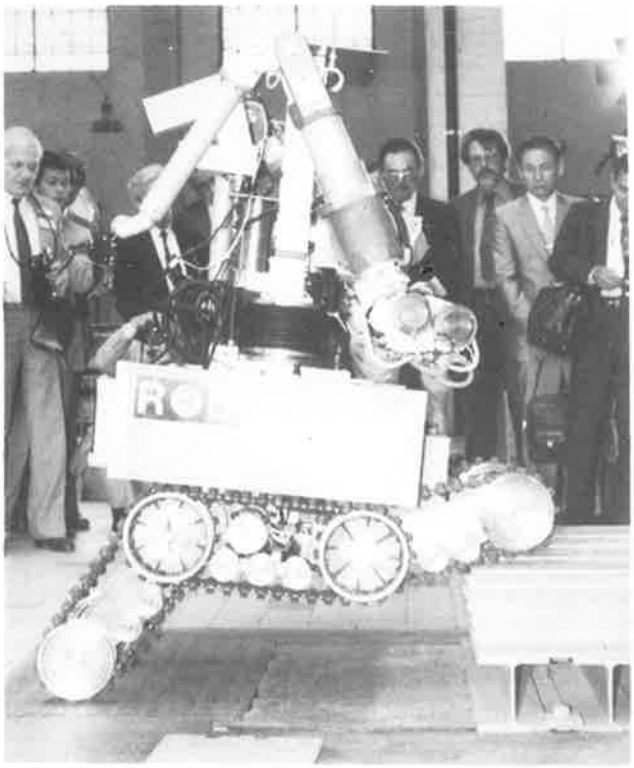
A completely new design from ORNL, the advanced servo-manipulator (ASM), has been built initially for the breeder reprocessing engineering test project. The ASM slave arm uses a torque tube transmission and is easily broken down into sub-assemblies to help maintenance and posting. Like the M2 and the SM229 at ORNL, the ASM is configured as a left and right pair of master-slave arms, working on remotely viewed tasks. Bilateral servo-manipulators also feature strongly as the appropriate teleoperated devices for US programmes in space and underwater.

ARP systems

Advanced robotics in nuclear engineering has been influenced by the Versailles economic summit of 1982. At that summit, the Technology Growth and Employment (TGE) Group proposed the framework for collaboration between the main industrialised nations in a series of technology areas, including advanced robotics. The advanced robotics programme (ARP), as it became, looked at many areas, including nuclear applications, for which France and Japan were the lead countries. More recently, Italy, Germany, and the UK have set up their own nuclear application ARPs.

The essential features of ARPs are the integration of artificial intelligence, complex sensors and vision processing, adaptive control, special materials, lightweight drives and transmissions, increased mobility, lightweight power supplies, and on-board computing power.

Non-nuclear applications tend to have a high degree of autonomy in their conceptual design. Nuclear applications, without exception, currently have limited autonomy, with most of the control achieved by operators through teleoperation. This is a key feature, even in the most advanced Japanese programme (the 1986 budget for nuclear power plant robot R and D was $6.3 million), which plans to have a total system built in 1990. The design proposes to use legged locomotion and relies on stereoscopic vision to achieve accurate deployment of manipulators and body motion. In the long term, machine 3D vision will be important for the totally autonomous system. In the short term, with human operators, reliance will be



ACEC's tracked-base robot vehicle.

Odetics' walking robot.

placed on conventional stereoscopic systems.

The choice of a locomotion subsystem will depend largely on the anticipated environment in which the advanced robot will operate. A simple extension to the tracked vehicles used for bomb disposal duties has been incorporated in the variable geometry vehicle constructed by ACEC of Belgium. ACEC developed the digital electronics for the Teleoperator Systems manipulators and MORFAX base and completed the systems engineering. Tracks were chosen so that the vehicle could climb stairs and negotiate minor obstacles. The target applications for the vehicle are reactor inspection and surveillance and response to accidents.

Research into walking machines is heavily funded by DARPA in the USA and MITI in Japan. Odetics Inc has been successful in developing a six-legged walking machine. The ODEX-1 was a prototype system. Later versions with manipulators (ODEX-2) and improved stability (ODEX-3) have been bought by Savannah River Laboratory and EPRI, as part of their experimental investigations. Odetics claims that \$100 000 to \$1 million can be saved now by the installation of a mobile robotic system in a nuclear power plant. It would perform only simple tasks such as routine testing, inspection, surveillance, and repair, which do not present any conflict with regulatory bodies.

At ORNL's Centre for Engineering Systems Advanced Research (CESAR) autonomous mobile robotics is being investigated for unstructured environments. The basic machine, HERMIES-II, is being used for concept demonstrations into navigation in the presence of moving obstacles. Special manipulator design for autonomous vehicles requires lightweight arms with high capacity to weight ratios. Such flexible arms need advanced methods of control which are computationally intensive, and this has resulted in developments in parallel and distributed processing using computing machines such as the hypercube. The hypercube used at CESAR has a potential configuration of 1024 separate processors which can run concurrently. The consequence of the design is that the hypercube has the capacity of 500 million floating point operations a second (500Mflops); each processor can run conventional computer programmes at about the speed of a VAX 11/780, with the overall computing tasks being evenly shared among the processors.

Advanced robotics for nuclear engineering is based on 40 years of specialised equipment development enhanced by recent progress in microelectronics, artificial intelligence, computing, and control. Although short-term solutions rely heavily on human supervision, intervention, and control, the scale of national programmes worldwide will ensure that fully autonomous operation is feasible and will be of value to a wide range of nuclear facilities. Even with the present state-of-the-art equipment, man-dose savings and economic benefits can be substantial. □

Dr Ed Abel works in the Engineering Projects Division of UKAEA's Harwell Laboratory, where he is responsible for the nuclear robotics and indirect viewing programmes. He graduated from Exeter University in 1971 with a first class Honours degree in Engineering Science, and began work commissioning large turbogenerators and superconducting machinery. Then as a Research Fellow at University of Warwick, he carried out contract research into the application of superconductivity to high speed guided ground transportation. Moving to UKAEA in 1979, he was initially involved in research into contactless power transfer and robotics. From 1981 to 1984 he was with the Atomic Energy Technical Branch.