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Robotic devices for future nuclear plant?

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Harwell Laboratory, Oxfordshire

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Starting point for nuclear advanced robotics programme...,

ROBOTIC DEVICES FOR FUTURE NUCLEAR PLANT?*

E Abel

ABSTRACT

Robots can present cost effective alternatives to man and conventional manipulators in nuclear facilities. The historical background to the development of servomanipulators and robots is reviewed, the types of application areas suited to robots are discussed, and recommendations are made for further developments. In the light of this review, a programme considering the use of robotic and teleoperated devices in nuclear environments commenced in August 1984 at AERE Harwell.

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INTRODUCTION

Harwell Laboratory has been involved in the development of remote systems for nuclear facilities over a period of many years. The emphasis has been placed on extending conventional master slave manipulator [MSM], shielding window, and filter technology, although novel alternatives to plant and equipment design have also been proposed.[1, 2] In recent years, the United Kingdom Atomic Energy Authority's Active Handling Programme has continued the conventional remote systems development, but has also fostered further research into alternative manipulative and remote viewing systems.[3]

While conventional through-the-wall MSMs and direct viewing are adequate for plant designed to existing standards, it has become increasingly difficult to match their capabilities to the task descriptions of facilities required for present and future fuel cycles. These facilities naturally require high availability and an assured consistent process throughput to maintain their economic viability. Similarly, decommissioning and waste storage activities require techniques for which the fixed manipulator-plus-window workstation is inappropriate. Finally, pressures to reduce operators' radiation exposure from Health Physics and Regulatory bodies are likely to limit the operating practices associated with through-the-wall MSMs and perhaps in the extreme might even curtail the option of penetration-based manipulators and adjacent handling.

The penalties of the fixed workstation and limited reach manipulator were recognized early on in the United States, and from 1954 Ray Goertz at Argonne National Laboratory [ANL] improved on the basic MSM design by electrically rather than mechanically linking the master and slave arms.[4] This radical change meant that the slave arm was no longer restricted to a position determined by the wall penetration, but was restricted only by the transportation device it was mounted on. Using ac servomotors as the actuators for the master and slave arm joints, Goertz provided a truely remote servomanipulator system, with force reflection. This philosophy was adopted by the nuclear industries in several other countries, but the concept has been largely ignored in the United Kingdom, where facility design required relatively minor modifications to the existing range of manipulators. Even so, UK utilities and manufacturers have designed and built complex machines for reactor refuelling, and specialized manipulators for inspection and repair of gas cooled reactors.[5, 6]

The UKAEA has begun to redefine its strategy for manipulator development. In doing so, cogniscence is taken of the recent rapid advances in microelectronics, computing and robotics, all of which have emerged as technologies in their own right, independent of the limiting constraint of low growth in the nuclear industry. Significantly, by adopting aspects of these technologies, it is possible to design remote handling systems whose components are the result of a much wider development effort, spread across many different industries. The starting point for the design of a manipulator or a servomanipulator is considerably different from 30 years ago, when there was virtually no recognized expertise appropriate to remote handling outside the nuclear industry.

The purpose of this paper is to review the historical background to servomanipulator and robot development, to consider the types of application areas suited to robots, and to identify the deficiencies that need to be overcome. From these considerations, the "Robotics" programme at AERE Harwell has been identified, and the initial year's work is nearing completion.

HISTORICAL BACKGROUND

Manipulators

The beginnings of master slave manipulator evolution in the nuclear industry can be traced back to an inverted U over-the-wall structure developed by Ray Goertz at the Argonne National Laboratory's Remote Control Engineering Division. The mechanism consisted of master and slave arms, connected by mechanical linkages, giving the operator all the feedback necessary to perform complex operations at a distance; it was first publicly displayed at ANL in 1949.[7] Work over the next few years, primarily at ANL, was directed at refining the transmission system to the tape and pulley, seven degrees of freedom, through-the-wall manipulator that has been widely copied throughout the industry and is still in common use today. The transmission medium had low friction and inertia, and proved ideal for Hot Lab applications. Increases in load handling capacity were achieved by stiffening the machine, and using roller chain as the transmission, [Figure 1] but the coverage of the slave arm was still limited to the volume immediately around the wall penetration.

The next development at ANL was the electric servomanipulator; four models [E1, E2, E3 and E4] represented progressive improvements in design. The E3 was the starting point for the Italian CNEN-Selenia development of the Mascot I and II servomanipulators.[8] Examples of these machines are in use at CERN[9] [Figure 2] and at the JET Undertaking at Culham.[10] The E4A[11] formed the basis of the Model M, [Figure 3] commercially available from Central Research Laboratory [CRL], who later undertook some modification of the electronics to reduce the heat dissipation in the ac servomotors.[12] A pair of Model M servomanipulators maintain and repair the accelerator targets at Fermilab[13] and their cost benefit in man-rem saving and straightforward monetary saving has recently been demostrated.[14] Perhaps of special importance are the two E2 machines at MIT, which formed the experimental test beds on which many postgraduate theses were based [for example, reference 15], and on which some of the early concepts of robotic theory that have now become standard practice were developed and verified.[16]

In the mid sixties, Carl Flatau developed the Brookhaven servomanipulator [Figure 4] which used a different control strategy of interlacing signals from force transducers as well as from position transducers. Dc servomotors were also used for the first time in the Brookhaven manipulator, resulting in a more compact drive package.[17,18] The practice of using dc rather than ac motors was continued in Flatau's SM229 manipulator,[19] and in Jean Vertut's MA22[20] and MA23[21] machines. All three machines retained the elbows-up attitude of the ANL E-Series, and used tapes and cables as the transmission media, with the motors at the shoulder. The SM229 has been used extensively for maintenance operations at the Los Alamos Meson Physics Facility,[22] where a pair of slave arms are mounted on a hydraulically powered boom. A pair of MA22 slaves were mounted on a remotely controlled vehicle, VIRGULE, [Figure 5] whose additional degrees of freedom meant that rescue or other complex tasks could be performed at a distance, outside of the normal fixed geometry of a Hot Lab containment.[23] About the same time, German development of servomanipulators produced prototypes for demonstration in Hot Labs and on an emergency vehicle.[24][Figure 6]

Vertut has continually refined the concept of telemanipulation based on the MA23, by optimizing the design [realized with the next model, the MA23M], to allow for easier maintenance.[25] He has also investigated CATS - computer aided teleoperation systems[26] and the application of the MA23M to the maintenance of future fusion reactors.[27] The last two developments anticipate the use of a servomanipulator in a robotic mode, where preprogrammed operation of the machines enhance normal man-in-the-loop control, improving efficiency, and reducing operator fatigue.

With the exception of the SM229 and the French development, servomanipulator technology stagnated after the close of the ANL programme. Machines were expensive compared to through-the-wall manipulators, especially when the necessary support and deployment systems and remote viewing were included. Because of the small number of development machines, reliability could not be adequately demonstrated and the servoelectronics was considered at the time to be an unnecessarily complex addition.

Recently the Japanese have developed several experimental servomanipulators which exhibit force reflection. Both the Japan Atomic Energy Research Institute[28] and Hitachi[29] manipulators are designed to go on vehicles, and both use direct force measurement on the slave for feedback via a computer to the master arm. In contrast, Meidensha Electric and the Power Reactor and Nuclear Fuel Development Corporation [PNC] have cooperated since 1978 to develop a series of force reflecting servomanipulators for use in high level liquid waste vitrification and FBR fuel reprocessing plant.[30] Several prototypes have been built and tested and application areas other than just nuclear plant are envisaged.

In the US, a revival of interest in teleoperation has centered in the Consolidated Fuel Reprocessing Program [CFRP] at Oak Ridge National Laboratory under US Department of Energy funding. Beginning with the Remotex concept,[31] which proposes that power manipulators be replaced with servomanipulators, and which also relies almost totally on remote viewing, the last five years have seen considerable progress.[32] Three full-sized mock-ups of remote maintenance facilities provide actual realistic demonstration of servomanipulators. The Breeder Reprocessing Engineering Test [BRET] project will incorporate the ORNL designed Advanced Servo Manipulator [ASM], a modular torque tube driven force reflecting servomanipulator.[33] The Remote Systems Development Facility [RSDF] uses a dual set of TeleOperator Systems SM229s on loan from Princeton Plasma Physics Laboratory, and has been used to evaluate many aspects of the effective use of servomanipulators.[34] The CFRP Remote Operations and Maintenance Demonstration Facility [ROMD] has been used to evaluate the CRL Model M2. The M2 is a recent joint development between CRL and ORNL where ORNL produced the all-digital control for the new CRL machine.[35] The mechanics of the M2 are directly derived from the E4A and model M machines, but the motors are brushless dc servomotors with rare earth permanent magnets.[Figure 7] The change in motors allows gross maximum orthogonal velocities to be virtually doubled compared to the original manipulator.[36]

Continued development at ORNL and in France will certainly bring force reflecting servomanipulators to the stage where proven reliable machines can be specified and procured on the world market for remote nuclear operations. These machines already exhibit a high degree of sensitivity in force reflection, and because of the adoption of digital control, they will also be amenable to robotic operation.

Robots

The development of robots can also be traced back to the early nuclear remote handling activities in the United States. In 1947, the first servoed electric power teleoperator [power manipulator] was produced, with the operator driving the end effector from a master control.[37] There was no force measurement or feedback [other than by viewing the machine's operation], and in many ways the device had the essential components of a robotic system, with the exception of programmability.

Despite this early start, and the continued development of power manipulators, it was not until 1956 that George Devol produced the concept on which the Industrial Robot Industry could be based. A prototype was built in 1959 and was applied in 1961, the same year that Devol's patent was issued, [38] and he formed the Unimation Company with Joe Engelberger.[39] Even so the company did not produce a profit until 1975. At that time the Robot Institute of America was formed although there was still no strong manufacturing base for robots.[40]

During this time several research laboratories were experimenting in the analysis and control of manipulators and robots.

In 1955, Denavit and Hartenberg produced a methodology for matrix representation of linkages that is now often used as the starting point for robot kinematic analysis.[41] In 1961 Ernst at MIT used a teleoperator slave arm under computer control to map out positional information using touch sensors on the jaws.[42] The robot did not have any preconception of position, and so the task was defined as a series of touch states.

Work at MIT and Stanford explored the possibility of using vision systems to define the positional information required for robot control.[43,44], but at this time no analysis existed to adequately map a robot's absolute position through to its respective joint angles. Pieper, again at Stanford, provided a solution to the joint angle-effector position problem.[45] He also noted that a wrist with three intersecting axes of rotation is one of the configurations which automatically allows an analytical inverse kinematic position calculation. For precisely this reason, many Industrial Robots have now been redesigned with "spherical wrists", which are effectively wrists with three intersecting axes. [Figure 8]

Whitney, in 1969 proposed a method of analysis which he called Resolved Motion Rate Control, which was necessary because he was using an E2 servomanipulator at MIT, which did not have a spherical wrist.[16] The inverse kinematic positions could not be calculated other than by numerical approximation and convergence, which is too slow for real time control of the manipulator. Whitney's method avoids calculating the inverse kinematic positions and instead used a precomputed set of inverse Jacobians to reduce the computational cost of matrix manipulation.[46]

By 1970 the Robotics community was sufficiently well established to hold the First National Symposium on Industrial Robots in Chicago. This grew into the annually held International Symposium on Industrial Robots [ISIR] whose venue rotates between the US, Japan and Europe.

In the early 1970s, control of robots was becoming more sophisticated, at least in the research laboratories. In 1972, Groome provided the first demonstration of force feedback control of a manipulator, where force sensing in several axes was used to determine levels of contact force [47]. About the same time, Paul at Stanford was developing a robot programming language, WAVE, designed to specify tasks symbolically in Cartesian coordinates and add constraints of position, force, touch, and vision feedback to the overall control.[48] The language was extensively tested on tasks performed by the Stanford Arm designed by Victor Scheinmann[49]. This electrically driven computer controlled arm has rotary motions and a prismatic motion similar to the early hydraulic Unimate series of robots.

With the increasing availability of faster and more compact processing, it at last became possible to take the broadly based laboratory expertise into industry. In 1976, Cincinnati Milacron developed and began to market the first computer controlled industrial robot.[50] The robot controller ensured that the tool point could move in straight lines so that it could interact directly with the motions of a moving conveyor. The basic robot function was taught with the conveyor at rest [to make it easier for the human operator] and then when the robot and process were running, the conveyor speed was fed directly into the controller, allowing conveyor tracking.

Also in the mid seventies, the advances in microelectronics had begun to produce small, low cost, high performance microprocessors. The impact of cheap fast computing on manipulators was that their control could be all digital, and that their performance could be rapidly changed to track changes in motion or payload.

Dubowsky described an adaptive control law formulated using a Model Referenced Adaptive Control System [MRACS] technique.[51] MRACS algorithms do not require complex mathematical models of the system dynamics nor a priori knowledge of the environment. They result in significant improvements in the dynamic performance of manipulators which are invariant with respect to changes in either the system configuration or the characteristics of the manipulated item.

Supporting the development of new laws for robot control, the analysis of robot kinematics and dynamics was consolidated in a book by Paul[52] and in a collection of papers edited by Brady.[53] Hollerbach and Featherstone extended their earlier work on the solution of inverse kinematics[54,55] and precisely identified the computational complexity involved for the major analytical methods. Finally, Hollerbach has proposed an efficient algorithm for calculating the inverse kinematic accelerations of a six degree of freedom manipulator with a spherical wrist[56] - the configuration that was noted for its importance by Pieper fifteen years earlier.

ROBOT APPLICATIONS

Hot Lab applications of robotics should be considered as a subdivision of the many nuclear applications, and this section illustrates the suitability of robots to aid exposure reductions and simplification of the task.

Immediate application of robotic devices in conventional nuclear power plant for routine testing, inspection, surveillance and repair can already be justified, and the savings over the design life of a robot might be between $100,000 to $1 million [57, 58]. Robots are now used extensively in PWR steam generator channel heads to inspect and repair the tubes [59], and have been considered for demilitarizing obsolete chemical munitions [60]. Currently available industrial robots could be modified to perform the following tasks [in order of increasing modification]:

- low level waste drum handling
- flask and pipework inspection
- CAGR/PWR/FBR fuel fabrication
- filter changing
- posting/bagging out operations
- decontamination
- glovebox decommissioning
- glovebox operations
- intermediate level waste drum handling.

For the levels of contamination and radiation associated with these tasks, it is not anticipated that major components of the robots would need modification. Modifications that might need to be made would be the addition of gaiters (booting) or alternative methods of contamination control, and the provision of a real time hand controller either for programming or teleoperation. As with any task, special purpose end effectors may need to be developed.

Details of several robot applications have recently been published, which are relevant to the Hot Lab fraternity.

- Remotely controlled manufacturing of mixed uranium/plutonium oxide fuel pins at Westinghouse Hanford [61]

- Remote waste removal and packaging from glove boxes at Savannah River Laboratory[62]

- Remotely operated cask handling system at Westinghouse Hanford [63]

The three applications are briefly described:

<u>Fuel Fabrication</u>

The Secure Automated Fabrication [SAF] line is designed to produce mixed uranium/plutonium oxide fuel pins for the Fast Flux Test Facility. The majority of operations are fully remote and with one exception, commercially available electric and pneumatic robots, without any major modification, perform the loading/unloading operations into specially designed fuel fabrication machines. The types of operation undertaken by the robots are pallet transfer of material, pellet transfer to a debinding furnace, pin loading and decontamination, chemical analysis, and general purpose workstation load/unloading. The facility is being commissioned and production is expected to begin in August 1986.

Waste Removal and Packaging

Chemical and metallurgical processing at Savannah River Laboratory, Shielded Cells Facility generates non recyclable solid waste which includes glassware, adsorbent towels and used test equipment. The waste is packed into one gallon paint cans, conveyed to a glove box and posted out. The outside of the cans are contaminated and cannot be handled directly. Health Physics surveys showed the surveying and posting of the cans generated significant radiation exposures and so the operation has been realigned to use a 10kg payload industrial robot. The robot uses a bagging technique to retrieve the cans and place them in a shielded drum. A separate automatic machine clips the PVC sleeve either end of the can. Future plans include automating other waste removal systems using prepackaged sleeves or a double door transfer system.

Cask Handling System

At a waste handling facility, cask surface doses may limit the throughput if personnel are required to work for extended periods of time close to the casks. Even with additional shielding in cask handling areas design targets cannot be met when multiple shipments per day must be handled. An analysis of the benefits of using robots to perform the cask handling processes determined that radiation exposure could be reduced by 94%, bringing the level down to the target of 1 rem/year. Typical tasks were cask washdown, survey, handling, gas sampling, and closure removal and installation. Part of the development has been to produce a simple method of controlling the particular robot chosen with man-in- the-loop control,[64] and to refine the man-machine interface.[65]

Extending the Range of Applications

The three applications cited above use industrial robots with very little modification, to work in mildly radioactive environments. It is natural to expect that a continued advantage could be gained if it were possible to extend the ability of robots to tolerate more extreme conditions. Before this can be achieved, deficiencies in the way existing robots are designed and are operated have to be resolved. Secondly, the environmental hazards have to be explicitly described, and thirdly, the tolerance of robotic subsystems to the environment must be understood.

The majority of robotic research is aimed at improving control algorithms or developing exotic sensors for vision, touch and feel. These developments often take five to ten years before they are incorporated into commercially available systems having a proven reliability. Improved control would be of immediate benefit, as it would allow error recovery, collision avoidance, higher level programming and trajectory control using sensory feedback. The Model Referenced Adaptive Control System already noted eases the computational burden in the robot controller, but is not as yet available outside the laboratory. The development of sensors has usually been at the expense of complexity at the end effector: this is the antithesis of good nuclear design principles. Most immediately, develoments are required for:

- Improving the teleoperator image - for successful human intervention and control.
- Force feedback to a master controller - for critical operations.
- Design modularity - to aid remote maintenance.
- Design for decontamination - resistance to acid cleaning and water jetting.
- Standardization of interfaces - so that common communication and software can be used.
- Robust viewing and sensing systems - to allow adequate control.

The addition of a master controller which provides force feedback to an operator inherently improves the teleoperator image over the common robot teach pendant. Several compound motion joysticks have been developed, but the most successful version has been developed by the Jet Propulsion Laboratory. Their Universal Hand Controller provides six degrees of freedom force feedback.[66] The controller is kinaesthetically dissimilar from the type of manipulator it controls - anything from a PUMA 560 to the Shuttle Manipulator - and the transformation is calculated in real time by a computer.

Design modularity ensures manageable sub-units which can be easily replaced and readily handled and posted through to maintenance or disposal routes. Decontamination design implies smooth surfaces devoid of contamination traps and requires leak tight sealed joints. These aspects have been examined in detail in the design of manipulators for gas cooled reactor inspection and repair[5, 6] as well as for conventional active handling machines.

Interface standards will dominate the choice of available equipment in the future. General Motor's Manufacturing Automation Protocol defines the method of interconnecting the computer systems which control automation and robotics, and is likely to become the de facto standard. Finally, remote viewing systems including stereo have been developed at Harwell specifically for the nuclear environment.[3]

Radiation presents the most severe environmental hazard, especially in the fuel processing facilities. Here, and during decontamination, the robot might also be heavily exposed to aggressive fluids. Dose rate is particular difficult to accurately specify in a large facility, as overall beta/gamma activity may vary by about eight order of magnitude. Those facilities which are concerned with alpha activity generally have low dose rates and total dosages, but require the robot to be designed to avoid contamination carry-over and to be easily decontaminated. The small sizes of laboratory glove boxes may often preclude efficient utilization of robots if retrofitted. As with the design of an Advanced Manufacturing Technology cell, the robot should be included as an integral part of the handling machinery, rather than as an add-on extra.

Every component of a robot should be examined to assess its radiation tolerance. A value of 10^4R is approximately correct for the total survivable dose, although the actual degradation might be gradual. Critical items would be:

- encoders (or other transducers),
- any electronics,
- organic material

- cable and connector insulation,
- seals,
- booting,
- lubricants.

Radiation testing allows estimates to be made for these critical items. A comprehensive data base does not exist for all these components, but would be necessary if widespread application of robots in the high radiation environment was envisaged. Data from space, military and accelerator sources is often not relevant because either the irradiation levels or energy spectra are different, or the dose rates do not match those expected in nuclear facilities. Fortunately, robot manufacturers have tended to modularize their products so that it is relatively easy to replace, for example, a motor-gearbox-brake-encoder package as a unit. This means that for supercritical components, a replacement-when-degraded strategy may give up to an order of magnitude mitigation against the total dose limit for the robot.

FUTURE DEVELOPMENTS

Robots that are used in 'fringe applications' of nuclear facility active handling have shown cost benefits in successfully reducing operational radiation exposures. Special purpose nuclear robots have proved invaluable in reducing exposure in reactor operations such as steam generator tube repairs and inspection. Any programme of work should attempt to extend their application by improving the basic design of industrial robots and understanding the consequences of the hostile environment. Harwell's programme has been to

- Establish guidelines for future plant and equipment specification.
- Indicate the direction in which medium and longer term R & D proposals should proceed.
- Provide the first stage of a comprehensive and co-ordinated programme in advanced robotics, teleoperators and process plant technology, relevant to the nuclear industry.

Main elements of the programme have been to quantify the data handling requirements, examine power and communications transfer within and into caves, study the man-machine interface, including such aspects as visual perception, image processing and stereo television, and establish a radiation tolerance data base and design philosophy. More recently, a study project has been evaluating the whole aspect of the integration of robots into the nuclear environment under the areas shown in Figure 9. The first year's results from this study are in the stages of final reporting.

CONCLUSIONS

This paper has surveyed the background of nuclear remote handling and its associated technology, robotics. It can be seen that there are many similarities between the complexities of design of both types of equipment, and in some cases adoption of a robot to perform tasks that previously were under manual control, or impossible, can show considerable advantages and savings in exposure dose and cost.

So far the applications have been restricted to mildly radioactive environments where only minor changes to a commercially available robot have been necessary, or in nuclear reactor plant where special purpose machines have been built for limited excursions into the primary circuit. Extending the range of applications will be possible by paying attention to

- Improving the man-machine interface and providing realistic easy-to-use controls for real time operation and programming.

- Improving the supporting systems such as sensing, including remote viewing.

- Designing for radiation tolerance using relevant data from representative radiation testing.

- Quantifying the environment in radiation or other hazard items.

- Ensuring that special purpose equipment conforms wherever possible to industrial standards.

- Equipment test of subcomponents and systems.

The in-depth analysis of an application is always necessary because robots are not designed for the type of environment considered here. It is however, possible to modify and adapt existing robots to suit a wide range of nuclear facility handling tasks, and this is being demonstrated successfully around the world in Hot Labs and Power Reactor Plant.

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FIGURE 1 - Through the Wall MSM with chain Transmission

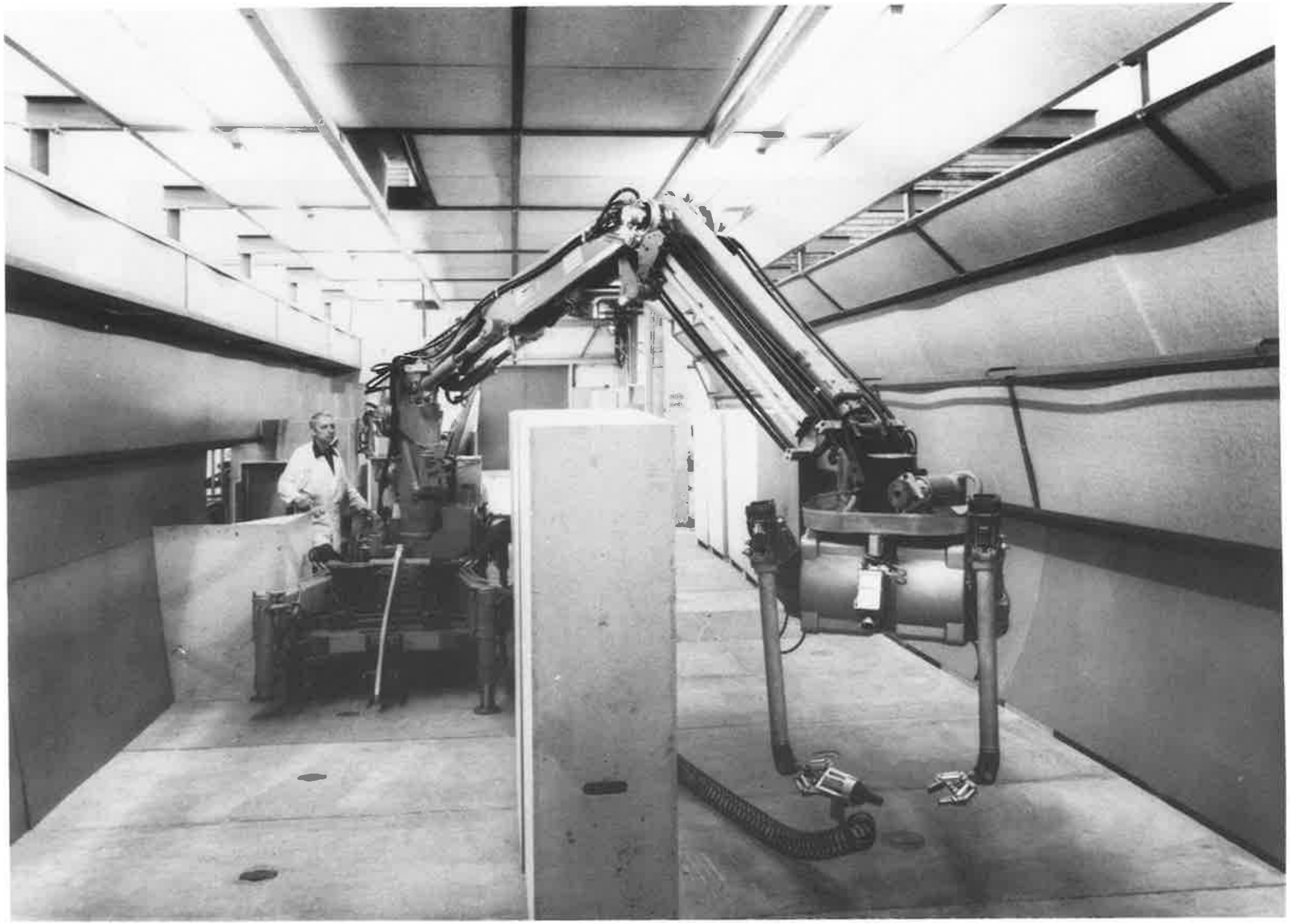

FIGURE 2 - MASCOT Servomanipulator at CERN

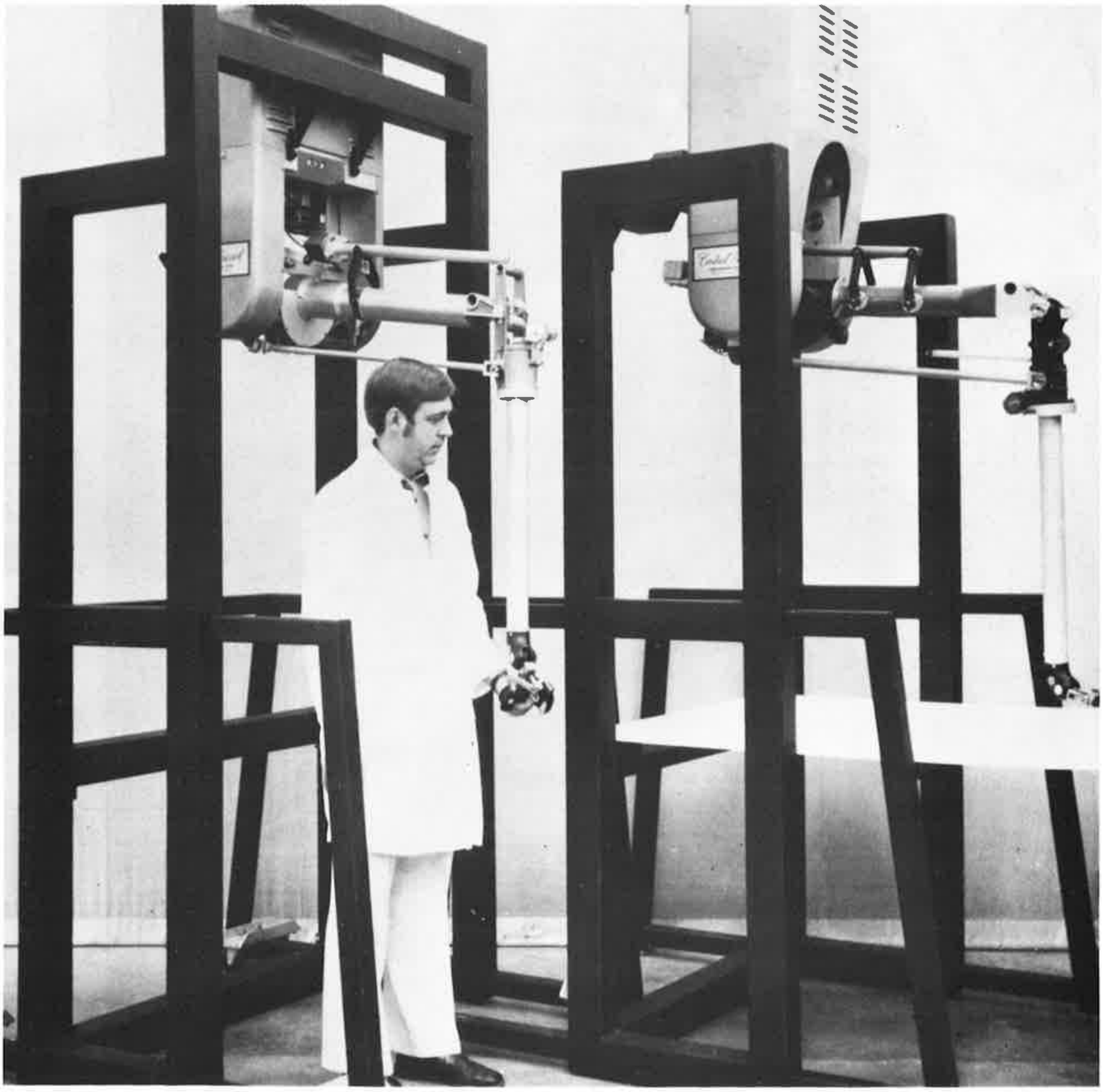

FIGURE 3 - CRL Model M Bilateral Force Reflecting Servomanipulator

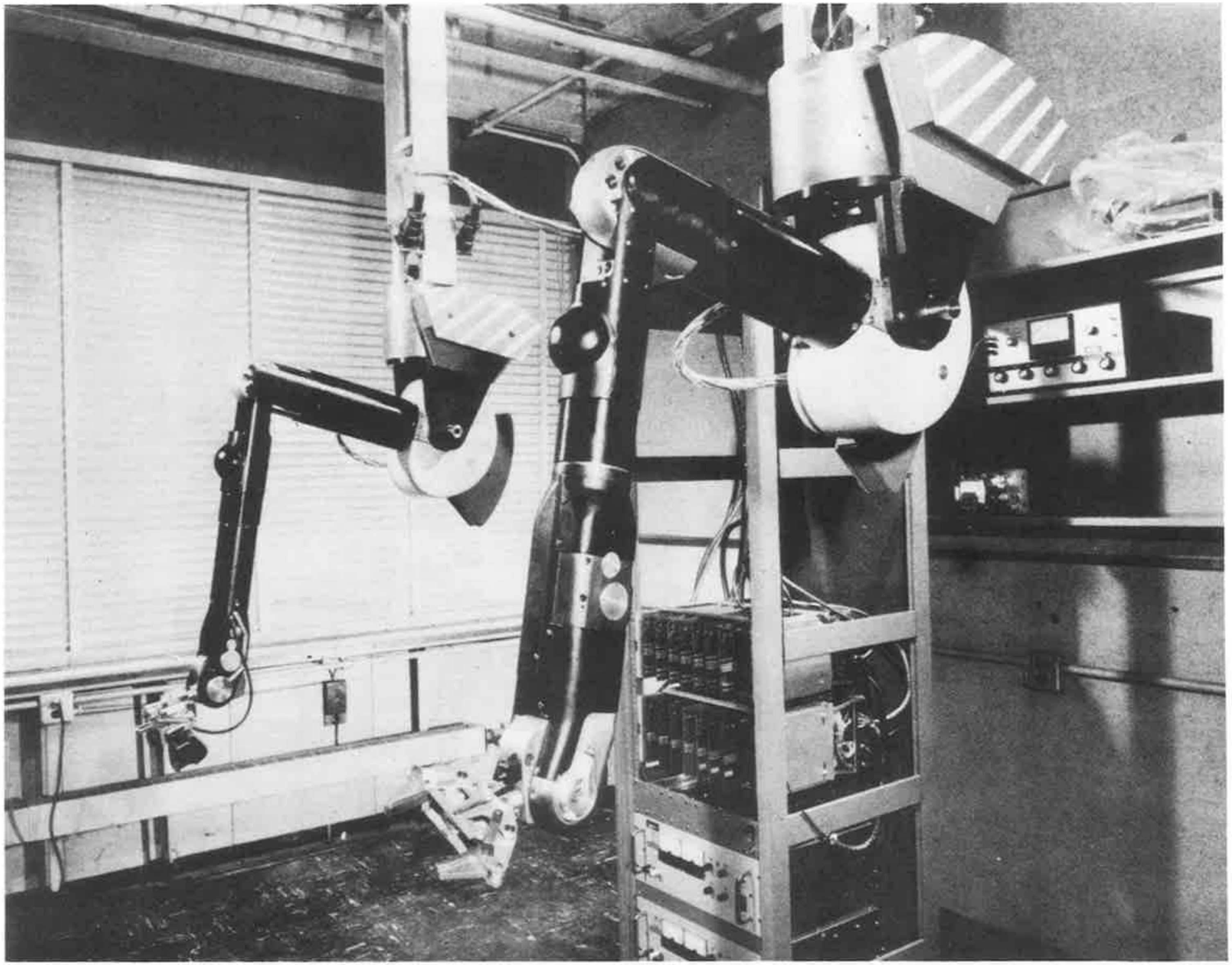

FIGURE 4 - The Brookhaven Manipulator

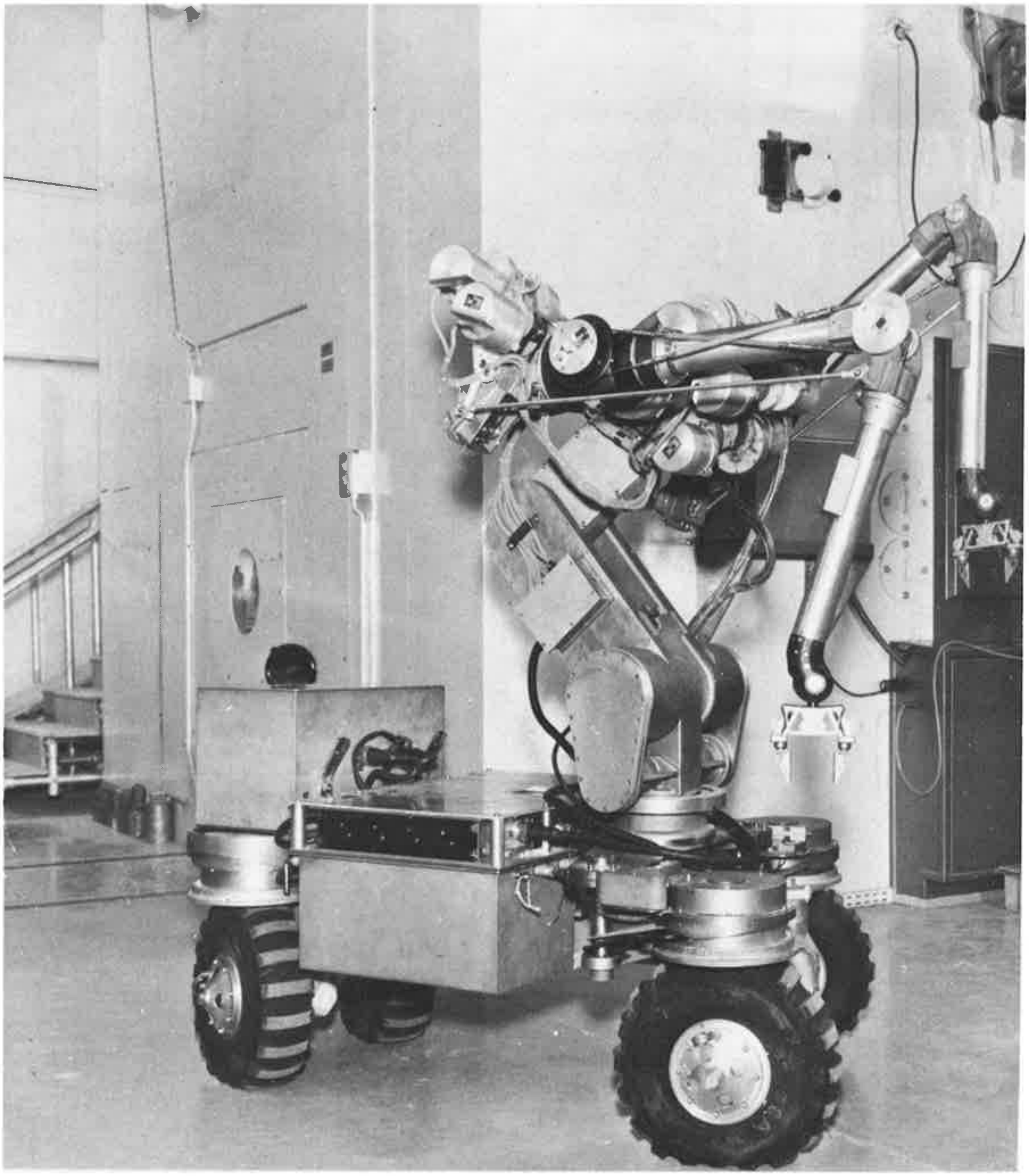

FIGURE 5 - VIRGULE

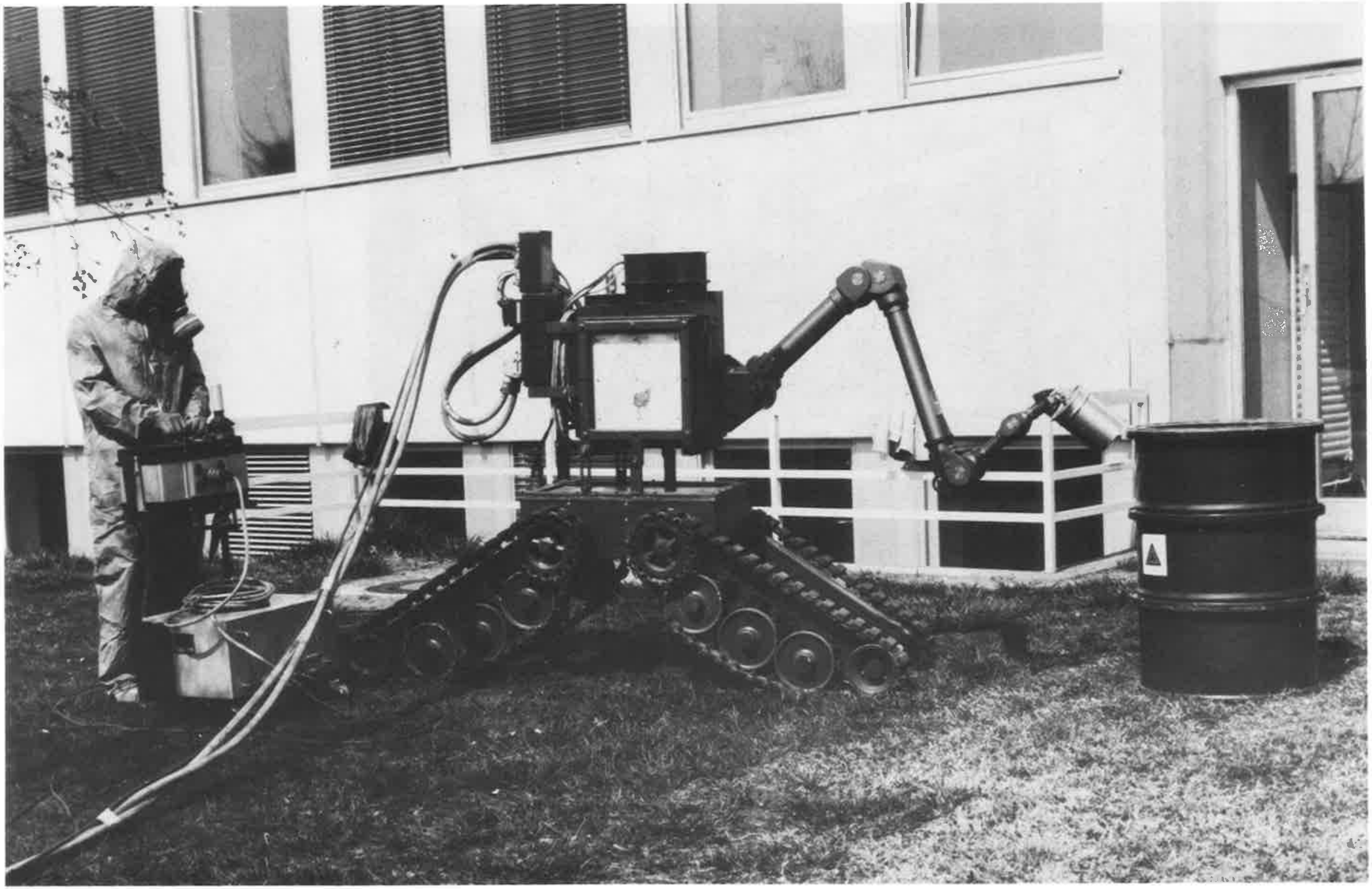

FIGURE 6 - German Emergency Vehicle

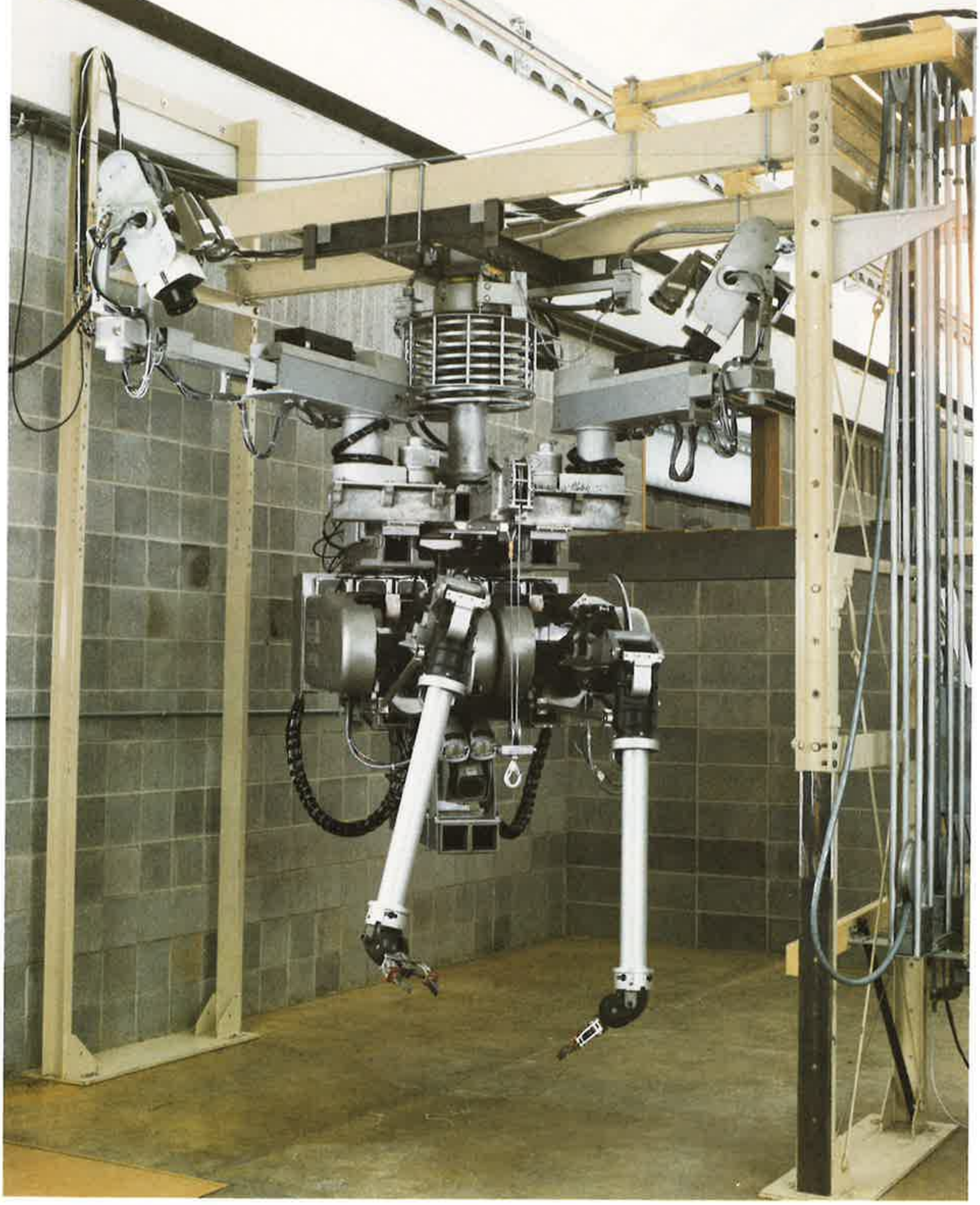

FIGURE 7 - CRL Model M2 Bilateral Force Reflecting Servomanipulator

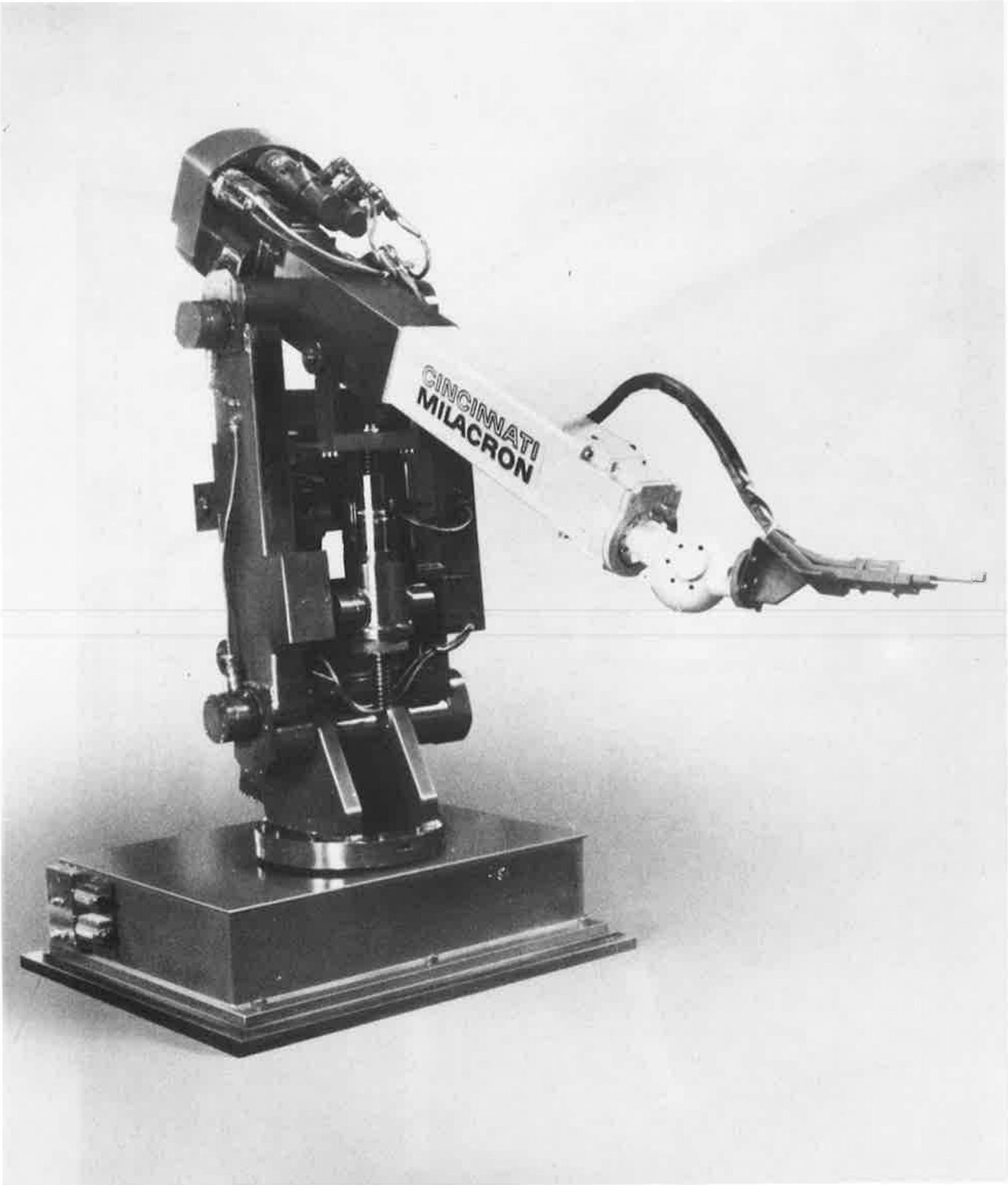

FIGURE 8 - Industrial Robot with Spherical Wrist

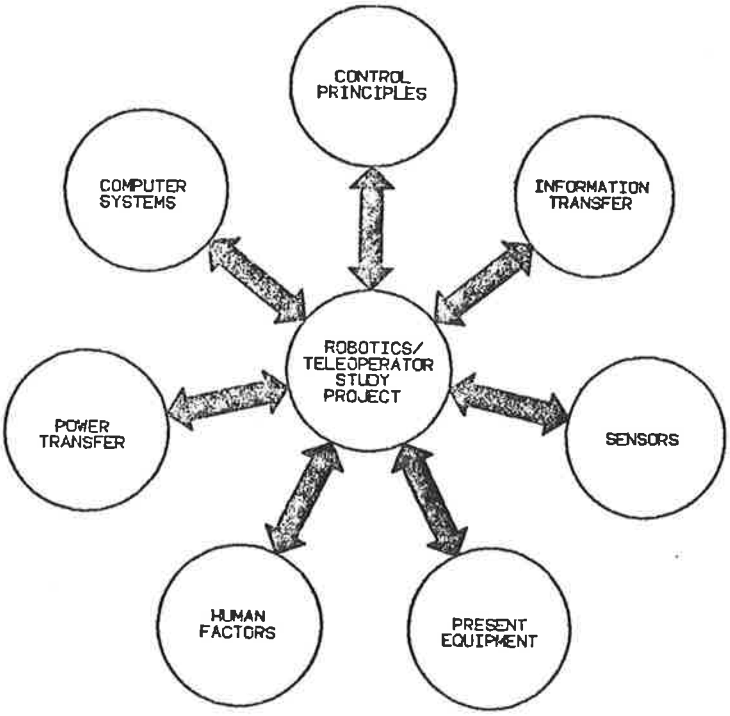

FIGURE 9 - Subdivision of the Study Project