6.11 Remote Maintenance Systems

Remote maintenance systems required in the IFE reactor of the year 2030 will be many and varied. In view of the pace of technological advance in remote handling, it is impossible to predict the maintenance equipment that may exist in that time. However, by considering today's devices and looking at current research, it is possible to speculate on what may be employed. Automation technologies will play a key role in attaining the goal of total remote maintenance. This section reviews the various technology areas that are pertinent to the remote maintenance task and indicates the research directions that may be relevant in the future maintenance device concept development.

6.11.1 Manipulator Technology - A number of current fission and fusion development projects have extensive remote handling capabilities that are state of the art. Figure 6.11-1 shows the ITER In-Vessel Vehicular System.[1] Though the ITER reactor does not yet exist, a number of prototypes of this device are under construction. ITER has a deployable rail on which 1-ton payload telescopic manipulators perform maintenance tasks such as divertor replacement. Figure 6.11-2 shows various manipulators working in the lower vessel area of the ITER machine[2] on typical tasks. The small manipulators shown are the Mascot and RD 500; the large manipulators are the SPAR telescopic and 2500 devices. Figure 6.11-3 shows the Joint European Torus Telescoping Articulating Remote Manipulator (TARM) and Articulating Boom Manipulators,[3] examples of equipment currently being used. Figure 6.11-4 shows the SPAR 2500 manipulator and a Schilling manipulator in use at the DOE environmental cleanup technology demonstration project at Hanford.[4]

6.11.1.1 <u>Master/Slave Telemanipulators</u> - Master/slave manipulators (MSM) have evolved in the nuclear and undersea remote handling areas over several decades from basic mechanically-coupled systems to electronically-coupled systems using electrically or hydraulically-powered slaves. Figure 6.11-5 shows the Mascot, a typical current nuclear MSM.[5] The main feature of these systems is the highly intuitive mapping between human motion commands and manipulator responses. This results in advantages over other teleoperation devices: (1) highly dexterous manipulators can be realized because the issues normally associated with dual manipulator coordination, kinematic redundancy (i.e., more than six joints per arm), and kinematic singularities ("lock-up" of mechanical degrees of freedom) are automatically and naturally resolved by the operator; (2) relatively complicated tasks can be performed faster with less training; and (3) computational requirements are simplified (or potentially eliminated) by the elimination of inverse kinematic transformation algorithms.

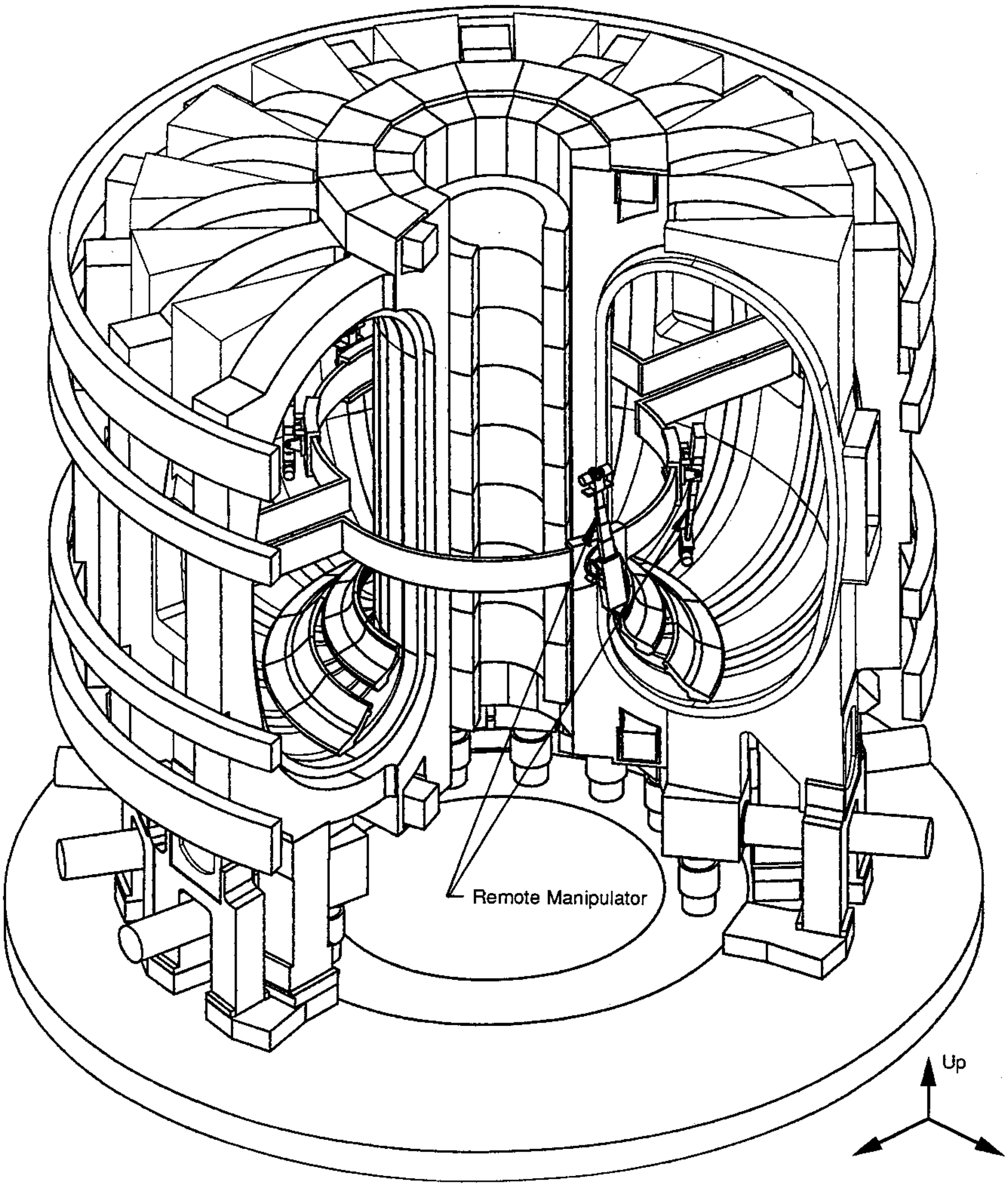


Figure 6.11-1. In-Vessel Vehicular System Represents Current State-of-the Art in Manipulator Technology

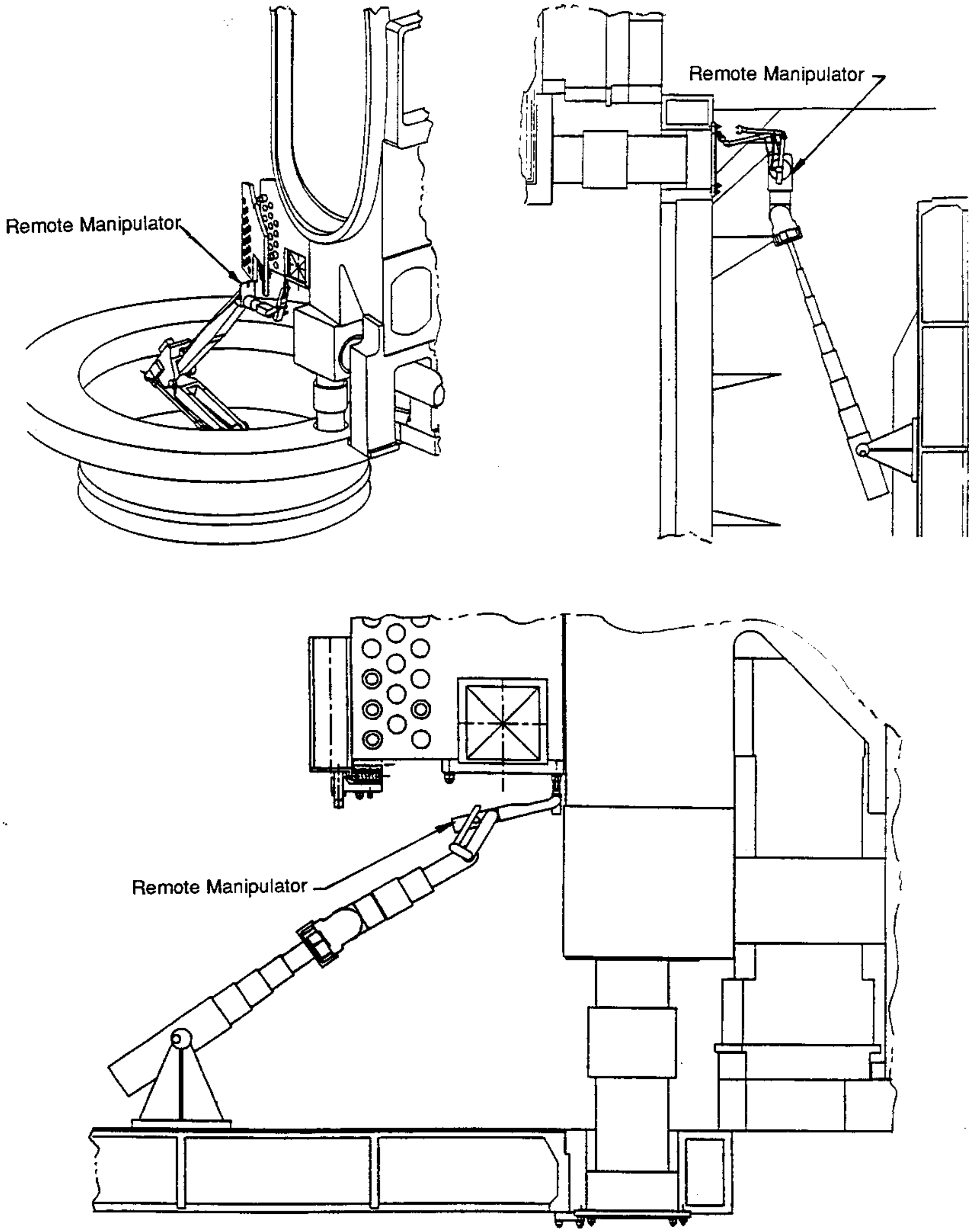


Figure 6.11-2. Remote Manipulators Performing Typical Maintenance Tasks on ITER

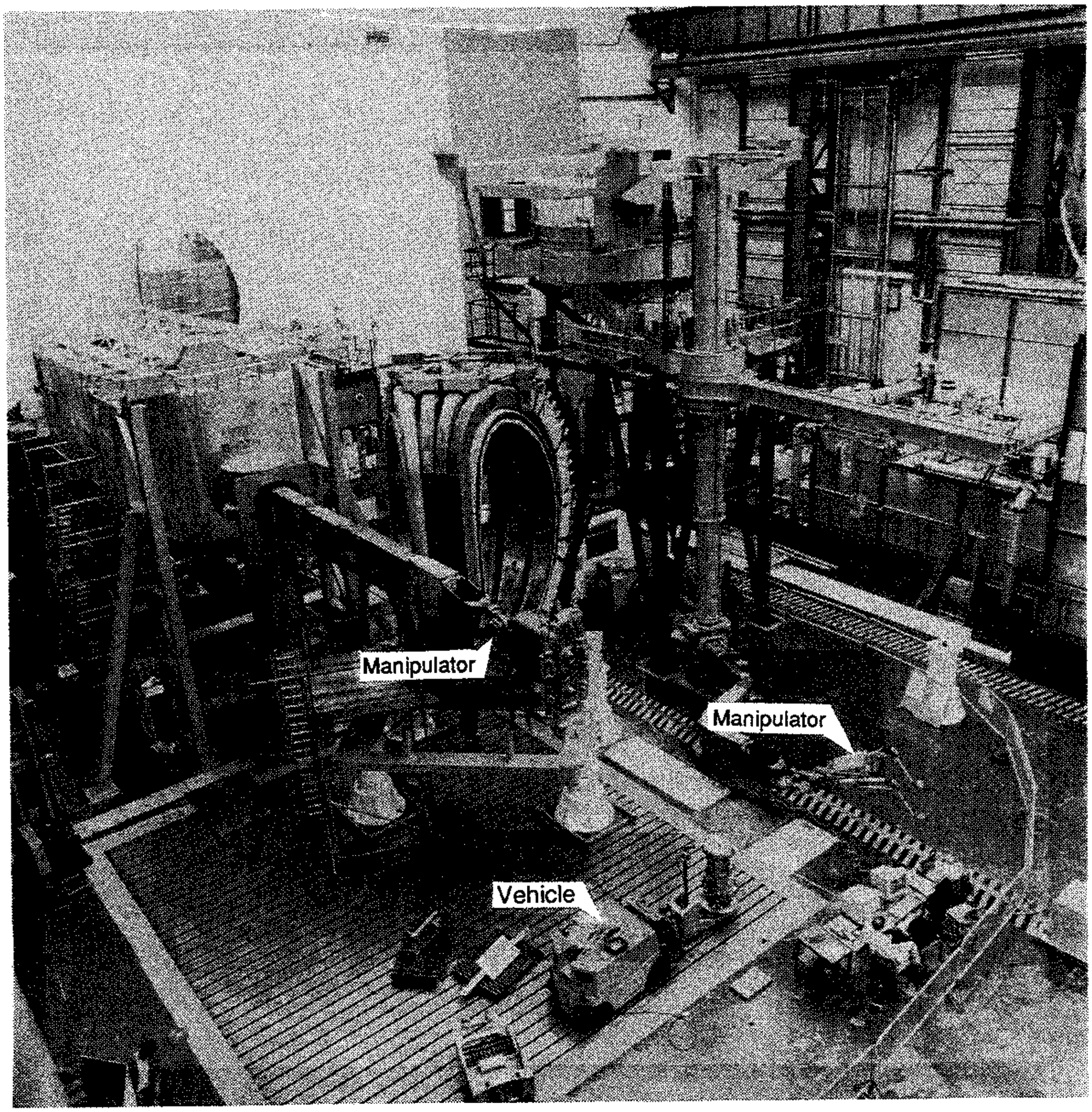


Figure 6.11-3. Maintenance Manipulators and Vehicle at the JET Facility

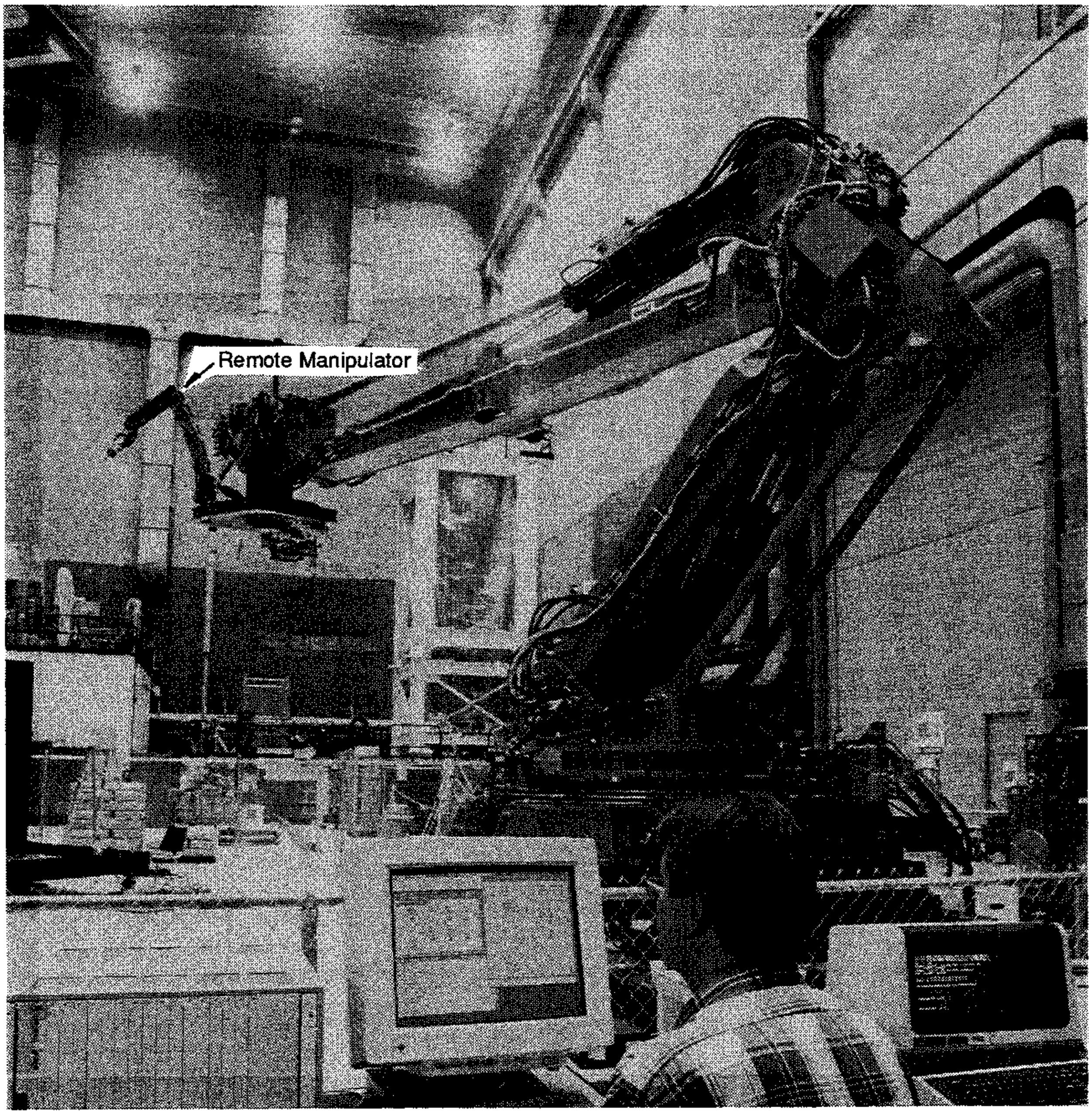


Figure 6.11-4. SPAR 2500 and Schilling Manipulator at the DOE Hanford Facility

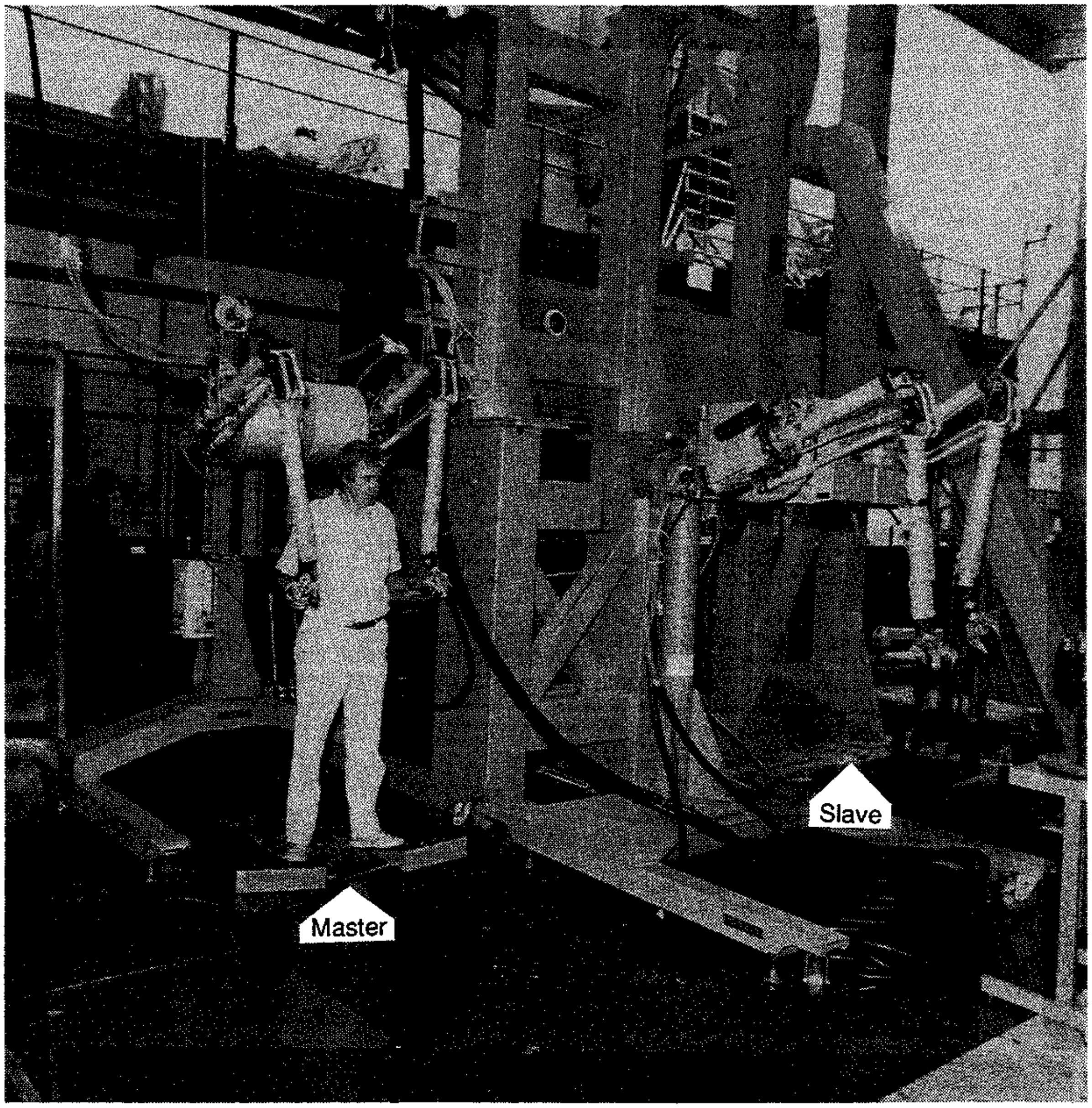


Figure 6.11-5. MASCOT, a Typical Small Nuclear Manipulator at the JET Fusion Facility

Master/slave systems are limited because they generally do not "scale" well. Loads and motions should be in a "human range." If the time scales are too long or the manipulator is too large, one-to-one teleoperation becomes tedious or potentially dangerous. The tasks need to be of the type that humans would typically perform with their own limbs.

Present development directions in master/slave systems include:

- Miniature (hand-operated) as opposed to full-size (exoskeleton) masters
- Improved force-reflection fidelity
- Ability to relocate control reference frames
- Faster, stronger, lighter slaves (advanced actuators and materials)

Master/slave systems will continue to be used in remote handling situations where the environment and tasks are relatively unstructured and unforeseen. In these situations the master/slave systems offer the closest possible alternative to direct human presence.

6.11.1.2 **Long-Reach Configurations** - Situations often call for particularly long-reach capability but may also exclude standard manipulator configurations because of size constraints imposed by the environment, access to the work space, etc. Several approaches to achieve a highly cantilevered manipulator body have been developed for applications such as the tokamak in-vessel remote handling and hazardous waste storage tank inspection. These devices are generally used in a coarse/fine mode where a large manipulator positions a payload and a small manipulator accomplishes the detailed handling or maintenance actions. Types of large manipulators are described below.

Telescopic Booms - These are typically used as the "vertical-axis" in standard Cartesian (gantry) or polar manipulator systems. They have been generally avoided where side-loading is an issue.

Deployable Trusses - Many ingenious deployable truss designs exist from simple "scissors geometry" to more sophisticated forms. They exhibit high stiffness to mass. Their geometry can be designed to deploy in either a straight line or an arc. Current research in truss designs employs actively controlled, variable-length truss links to permit full six-degree-of-freedom motion capability. Figure 6.11-6 shows typical deployable trusses that are available and currently used.[6]

STEM Mechanisms - Storage Tubular Extendible Member (STEM) mechanisms are limited in stiffness and strength. However they offer an extremely high ratio of deployed length to stowed length and can deploy or retract quickly. They are suitable for tasks such as camera/lighting positioning. Figure 6.11-7 shows the method to deploy a STEM element. Figure 6.11-8 shows a typical STEM application with a camera.

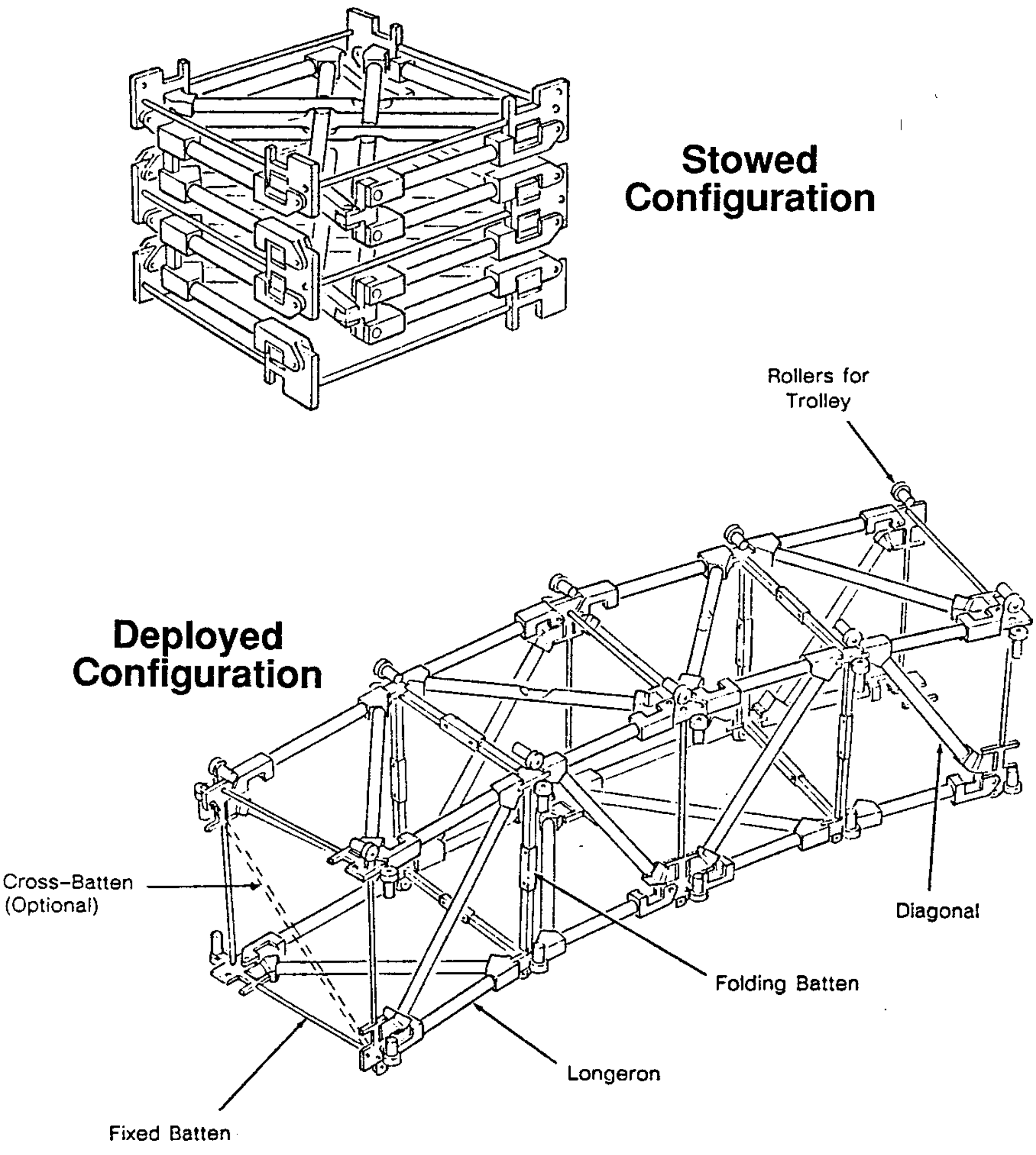


Figure 6.11-6. Curved Deployable X-Boom Truss

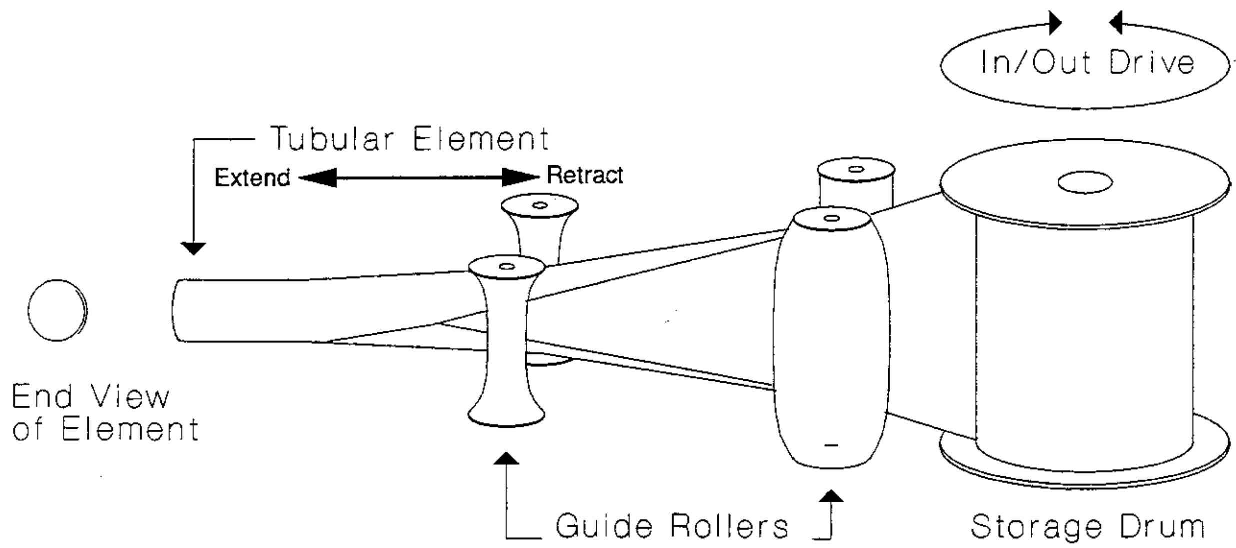


Figure 6.11-7. STEM Element Deployment

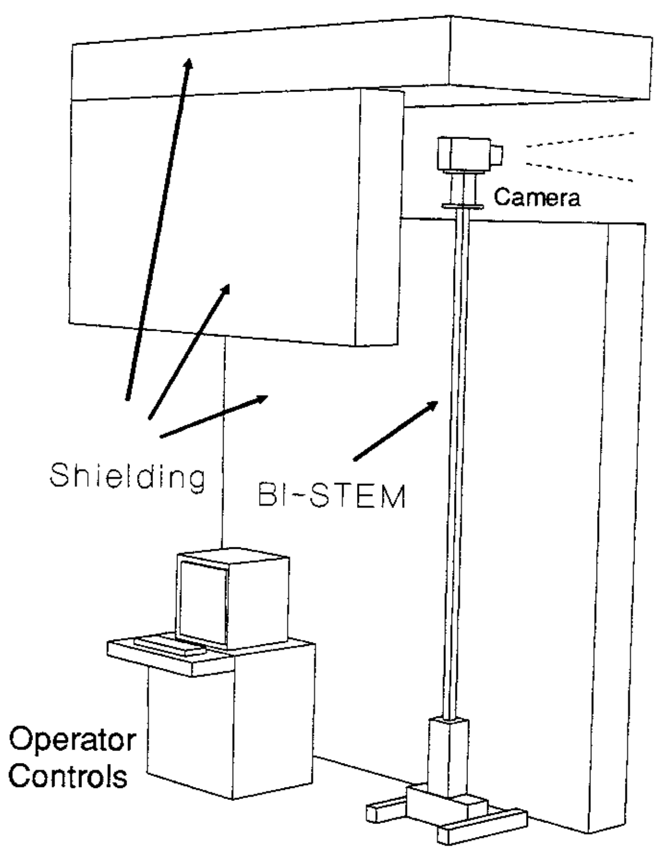


Figure 6.11-8. STEM Mounted Camera

Articulated Boom Mechanisms - Articulated boom mechanisms were developed for servicing the interior volumes of tokamak reactors. They offer high cantilever stiffness and strength for their cross-section. They can be controlled to "bend" to avoid obstacles, go around corners, etc.

6.11.1.3 Large Payload Manipulators - When large, heavy payloads must be handled in a relatively dexterous manner (that is, where simultaneous control over several degrees of motion freedom is required), large serial link manipulators with hydraulic actuation are employed. With appropriate resolved motion control, such manipulators are capable of fairly precise trajectory following and positioning with resolutions to 1 cm.

Current large payload manipulator research is directed toward adding force-sensitive control and improved teleoperator interfaces.

6.11.2 Transport/Handling Technology

6.11.2.1 Mobile Platforms - Automatically guided mobile platforms are used to transport loads over relatively long distances and generally involve fixed paths if not restricted right-of-ways. There are examples of mobile platforms with load capacities as small as a few kilograms to as large as hundreds of tonnes. For payloads of up to a few tonnes, battery-powered electric propulsion is common but has the problem of frequent charging requirements and limited battery life. Propane-fueled combustion engines can ease, but not eliminate, the maintenance problem. A third alternative uses passive platforms with in-floor linear induction motor propulsion. Such systems have been proven in industrial handling applications, and while more costly, offer superior reliability, very low maintenance, higher payload capacity, and faster throughput. Belt and powered roller conveyer systems are generally too maintenance intensive to be considered for essentially human-free applications.

Current development directions in mobile platforms are to add more sophisticated self-navigation capability, including obstacle avoidance and real-time path planning. Automatic battery-charging/replacement systems, load-vehicle transfer systems, and supervisory control systems continue to be improved. Some development work has added manipulator capability to mobile platforms, but portable power capability remains a limiting issue for such systems.

6.11.2.2 Crawlers/Inspection Robots - Small mobile "robots" for traversing the interiors of pipes, ducts, and other severely confined areas have been developed. These generally have little or no manipulation capability but can carry cameras or other sensors for inspection purposes. In some situations, they could carry tools for welding, lubricant dispensing, etc. Examples of self-powered robots with telemetry control links exist, but trailing tethers are commonly used to provide power and data channels.

6.11.2.3 **Tracked/Legged Robots** - Tracked and legged approaches to robot locomotion have been developed to improve negotiation of obstacles, stairs, etc. The robots tend to be relatively slow and inefficient in terms of power use. If the plant infrastructure is designed with a total remote maintenance concept in place, the use of such robots will be minimized or eliminated.

6.11.2.4 **Overhead Systems** - Overhead gantry systems offer single or two-dimensional positioning of manipulators or the handling of large items over a large work space area. They can accommodate several ton loads. Current overhead handling systems offer POSI-CAST® control algorithms for much more stable and rapid hook positioning than is possible with purely manual operator control. Truss technology has been integrated to produce deployable cranes which allow either the complete crane or just its drives to be removed from an active environment when not in use. Figures 6.11-9, 6.11-10, and 6.11-11 show typical deployable cranes.

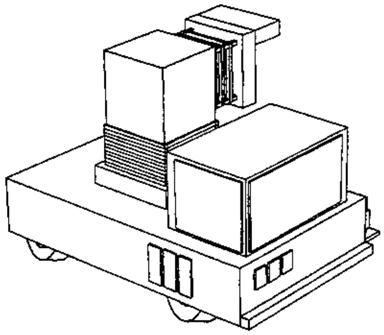
6.11.2.5 **Elevator Systems** - Scissors-lift and hydraulic elevator systems generally offer higher capacity and reliability than cable-driven systems. However they are generally limited in lift distance—typically less than 10 m.

6.11.3 Automatic Control Technology

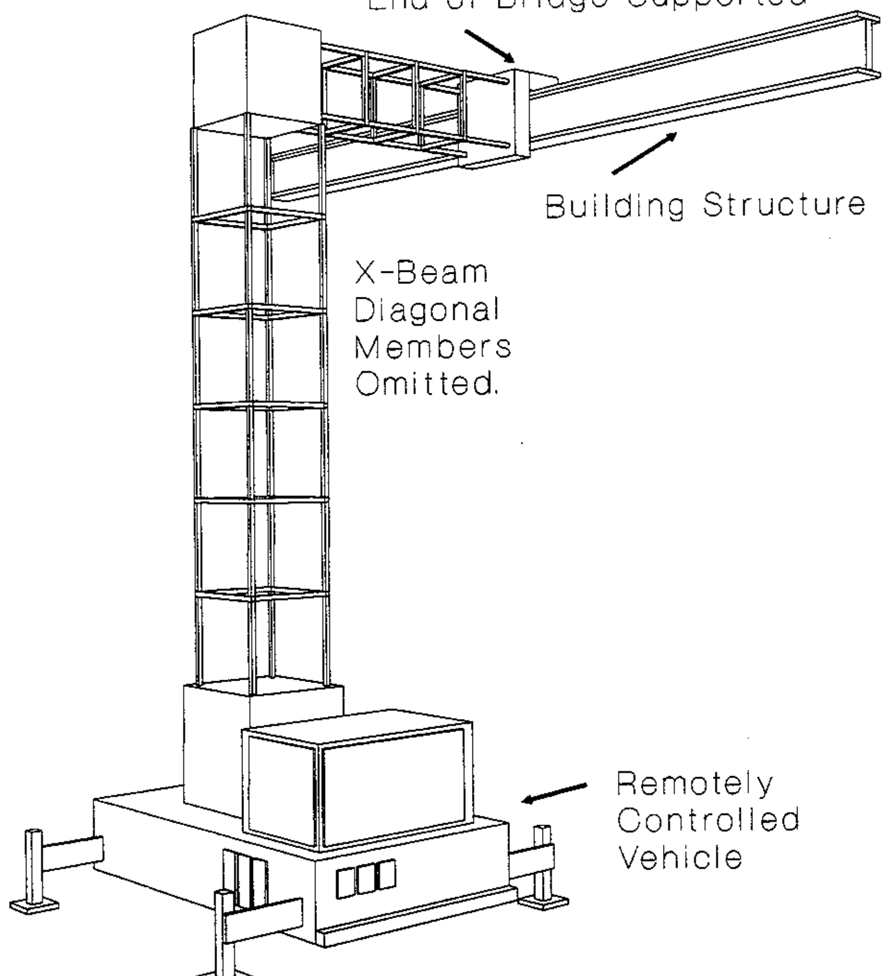
6.11.3.1 **Sensing and Control** - The general trend in robotic technology has been toward increased autonomous capability. This has often involved the addition of more and better sensing and control loops. The pertinent areas are detailed below.

Robot Vision - Present capabilities in robot vision mostly relate to the recognition and spatial "acquisition" of known targets through closed-circuit television imaging for the purposes of referencing motion commands. An example of this would be the tracking of a moving target or planning the grasping of an object. Research directions include increasing use of laser-based imaging systems for creating true 3-D image maps.

Force Control - Whereas conventional robot control has been motion-based, there is an increasing trend toward force-sensitive and "active compliance" control strategies. These offer advantages in manipulation involving stiff contact and in situations where "accidental contact" could occur. Research is continuing in the areas of improved joint level sensing and higher bandwidth control.



Folded for Transport



Deployed Configruation

Figure 6.11-9. Mobile Folding Crane

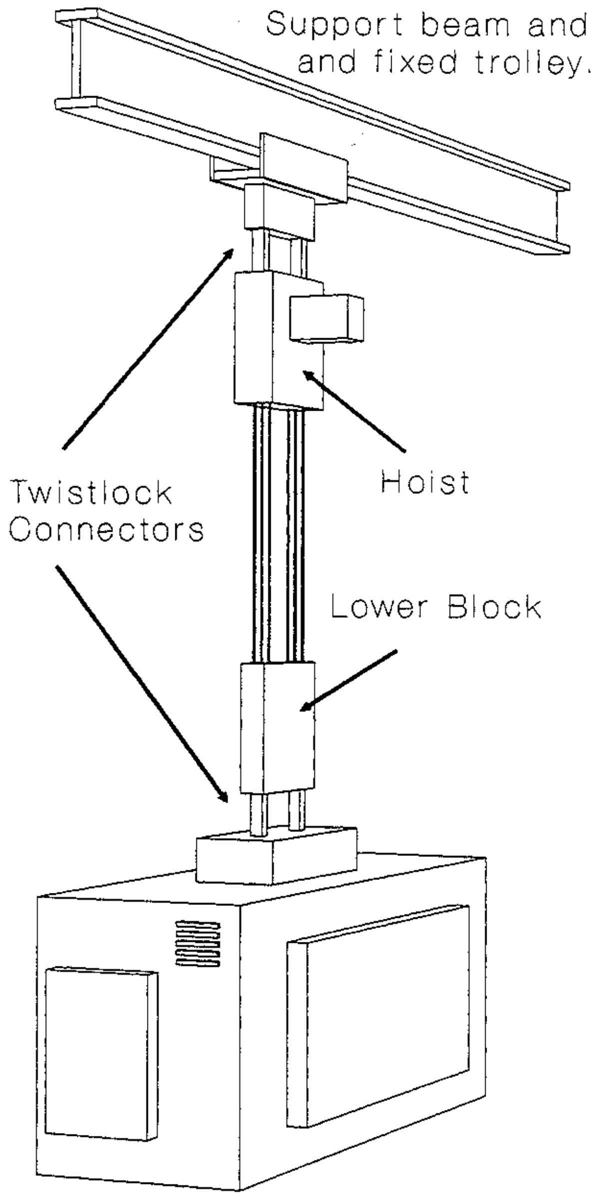


Figure 6.11-10. Deployable Crane Hoist

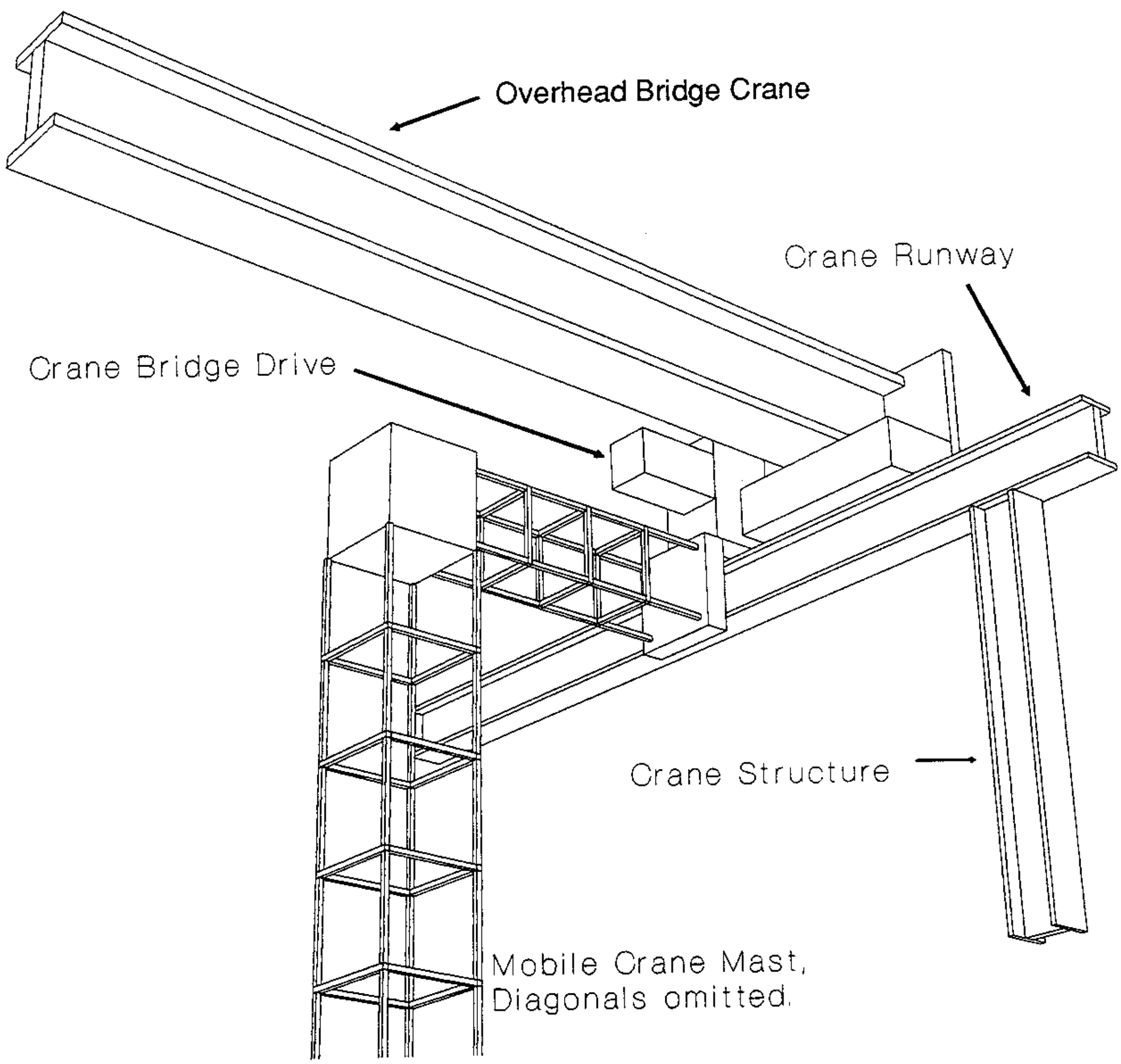


Figure 6.11-11. Heavy Crane with Removable Drives

Tactile Feedback - Feedback via "tactile sensing arrays" allows sensing and control to acquire detailed surface information through "touch." Present examples of this technology are restricted to research labs. Such technology could be used in the reactor maintenance system through the use of a control algorithm designed for seam-tracking or edge-finding.

6.11.3.2 Robot "Intelligence" and Task Level Control - At one time it was assumed the limits of a robot's "cognitive" capabilities were due to hardware computational limits. It is now more widely recognized that the limitations are algorithmic. Research continues in the so-called AI domain, but in spite of names like "neural networks" and "heuristic reasoning," the expectations are now more modest. It is likely that robots will continue to improve but not become necessarily "smarter" over the next few decades. Traditional areas of higher level robot control such as real-time path planning and collision avoidance will continue to develop. Also, improvements in older programming methods such as "teach/trace" will continue as more kinds of sensory data and improved computer graphic simulation are integrated into the procedures.

6.11.3.3 Human-Machine Interface Technology - An area of particular significance for teleoperated remote systems is in the human-machine interface. Considerable research effort is being conducted in the areas of 3-D vision feedback, force, and tactile and auditory feedback, stimulated by rapid change of the applicable technologies. The relatively new concept of stereo television is being replaced by head-mounted wide-field displays. The head-mounted camera enables views that change in response to head and eye movement. These developments will ultimately enable master/slave teleoperation maintenance tasks to be quicker and more effective.

6.11.4 Tools - Tools are a key part of remote handling technology as evidenced by a large proportion of current development budgets being devoted to them. They are generally specific to applications. Figure 6.11-12 shows a JET cutter that is typical of a special application tool.

6.11.5 Principal Plant Manipulators

6.11.5.1 Overhead Bridge-Mounted Manipulator - The overhead bridge-mounted manipulator is located above the reactor. It has a working volume bounded by the projected area above the reactor and the inner wall of the biological shield. Figure 6.11-13 illustrates a typical overhead bridge crane with a manipulator.

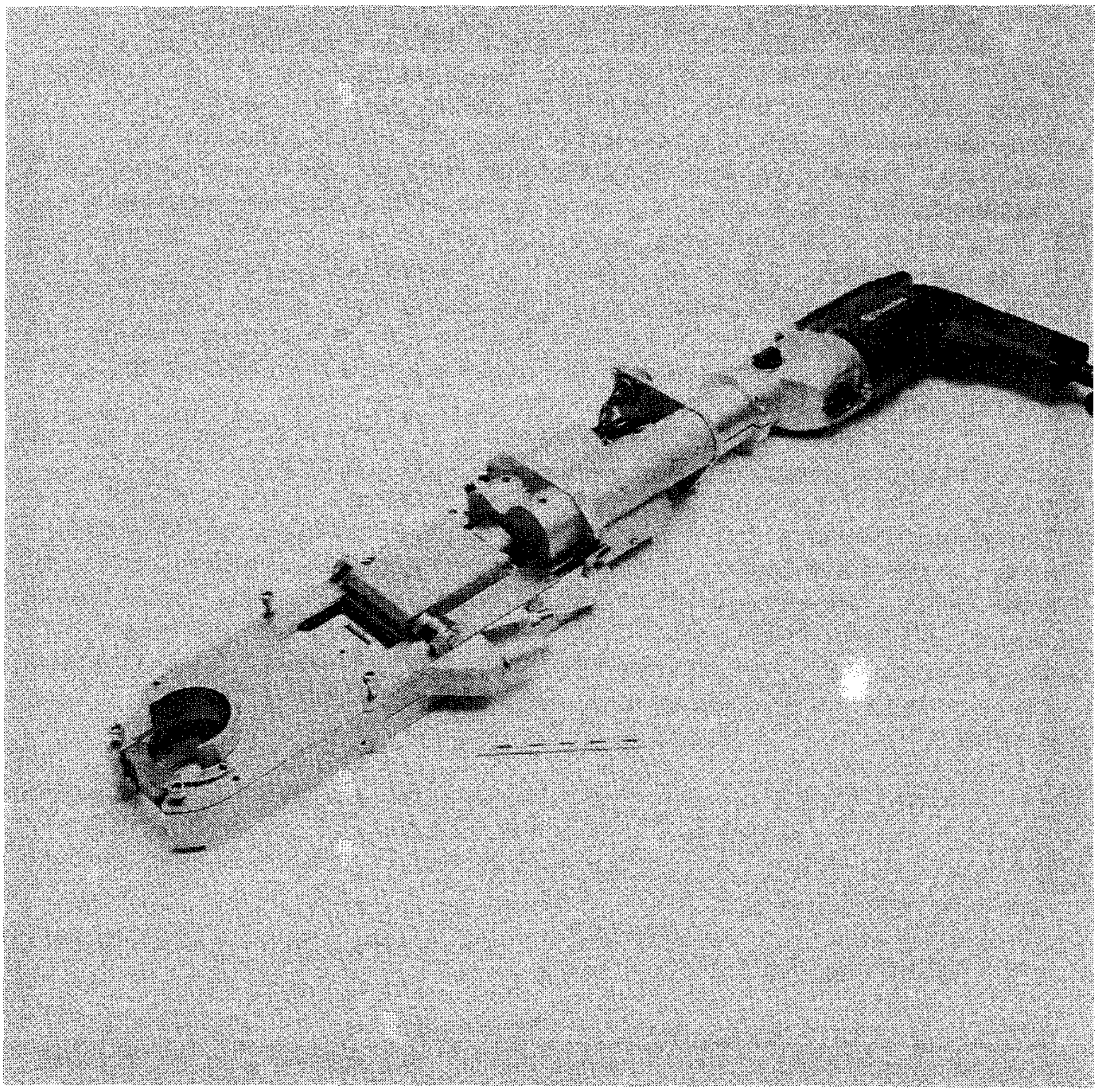


Figure 6.11-12. Typical Remote Handling Tool (JET Pipe Cutter)

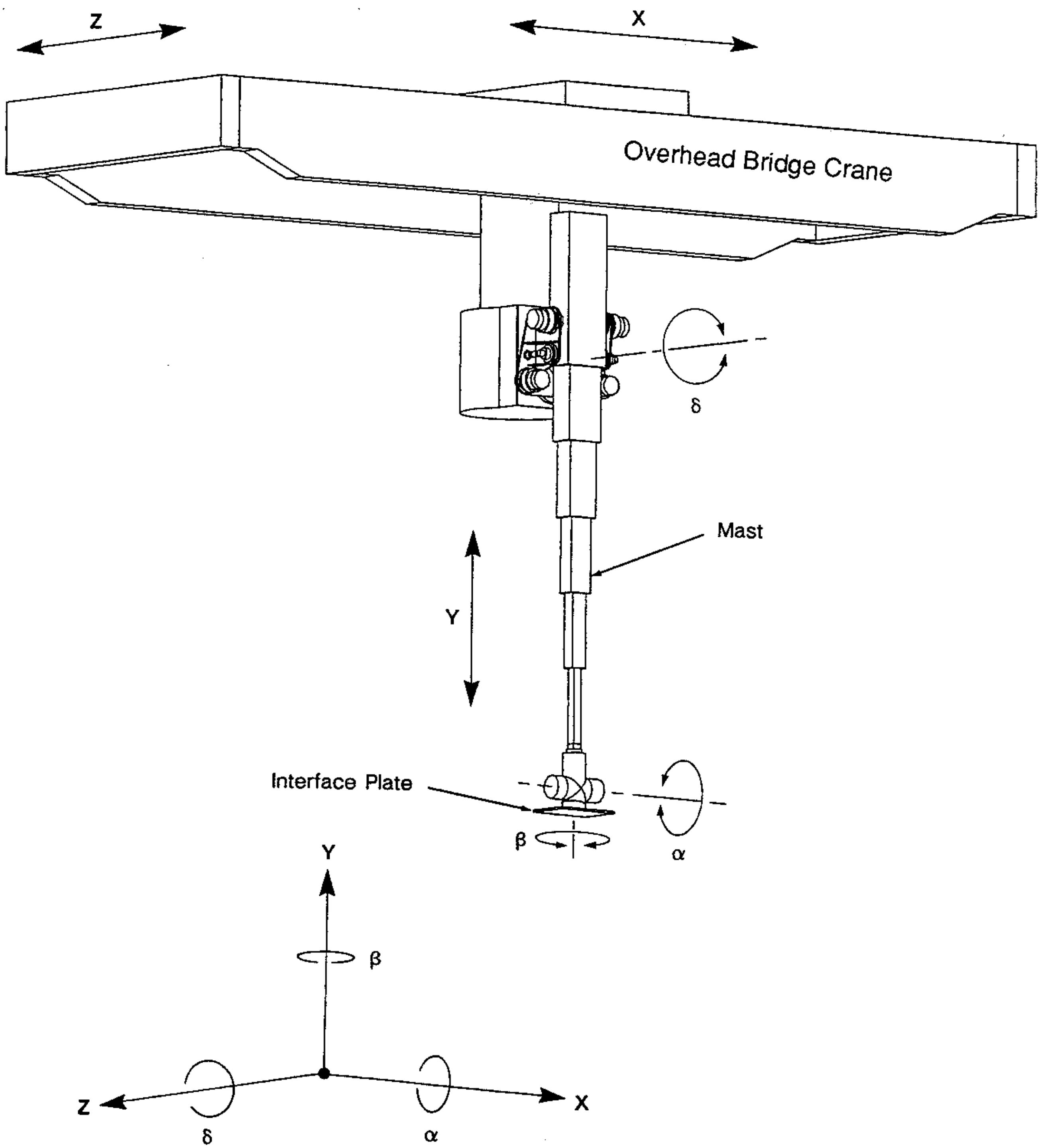


Figure 6.11-13. Upper Reactor Manipulator

The manipulator is used to provide maintenance support when working on the external components of the reactor. It can also be used internal to the reactor when the upper hemisphere is removed.

The manipulator trolley is located on the bridge crane and supports the telescopic mast. The trolley has a turn-table drive that provides ±360° rotation. The mast is attached to the trolley via a rotational joint that provides a limited angular rotation.

The unit is a general purpose transporter that can supply dexterous manipulator capability and tools required when maintaining the upper section of the machine. It has an interface that can connect to the power and dexterous manipulators.

6.11.5.2 **Deployable Heavy Lift Manipulator** - The deployable heavy lift manipulator is shown in Figure 6.11-14. It has two major links attached to a rotary base. The base and link structure are detachable for easy transport to the work site. The base is transported to the work site and the stabilizers deployed to form a rigid base. The arm and lower pitch joint are transported separately and assembled on site.

The device is normally used for the maintenance of components that have access at ground level or below. It has power supplies and an interface plate that can mount a dexterous or power manipulator. The interface plate can also support heavy duty tools or dedicated maintenance machines for remote cutting and welding.

The links can be hydraulic or electrically actuated. If hydraulic fluid contamination is a problem, electrical screw jacks are provided. For heavy loads, hydraulic actuators provide a better load-to-weight ratio. The rotary yaw joint can be electrically or hydraulically driven. Three modes of control are provided:

- Preprogrammed automatic
- Teach and repeat
- Man-in-the-loop

6.11.5.3 **Mobile Heavy Duty Manipulator** - The mobile heavy duty manipulator is a self-driven device that is normally located away from the reactor and remotely deployed to the work site when required (see Figure 6.11-15). It has a lower lift capacity than the deployable manipulator. In position, stabilizers are deployed to form a steady base. The base houses the rotary drive and the transport system. It is used in areas where a clear access is provided for travel. It is normally used where access can be gained from below or from the side at ground level.

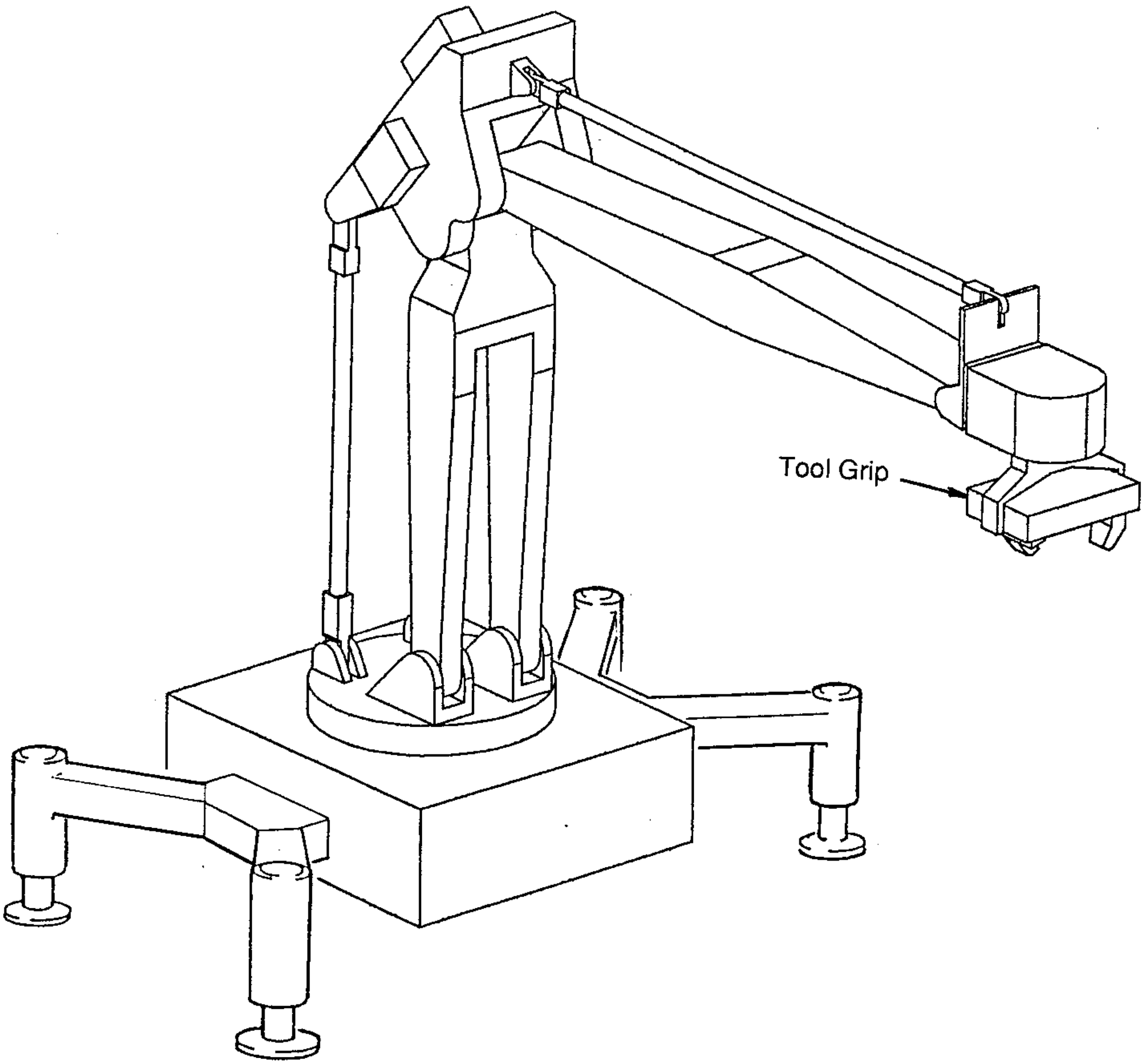


Figure 6.11-14. Deployable Heavy Duty Manipulator

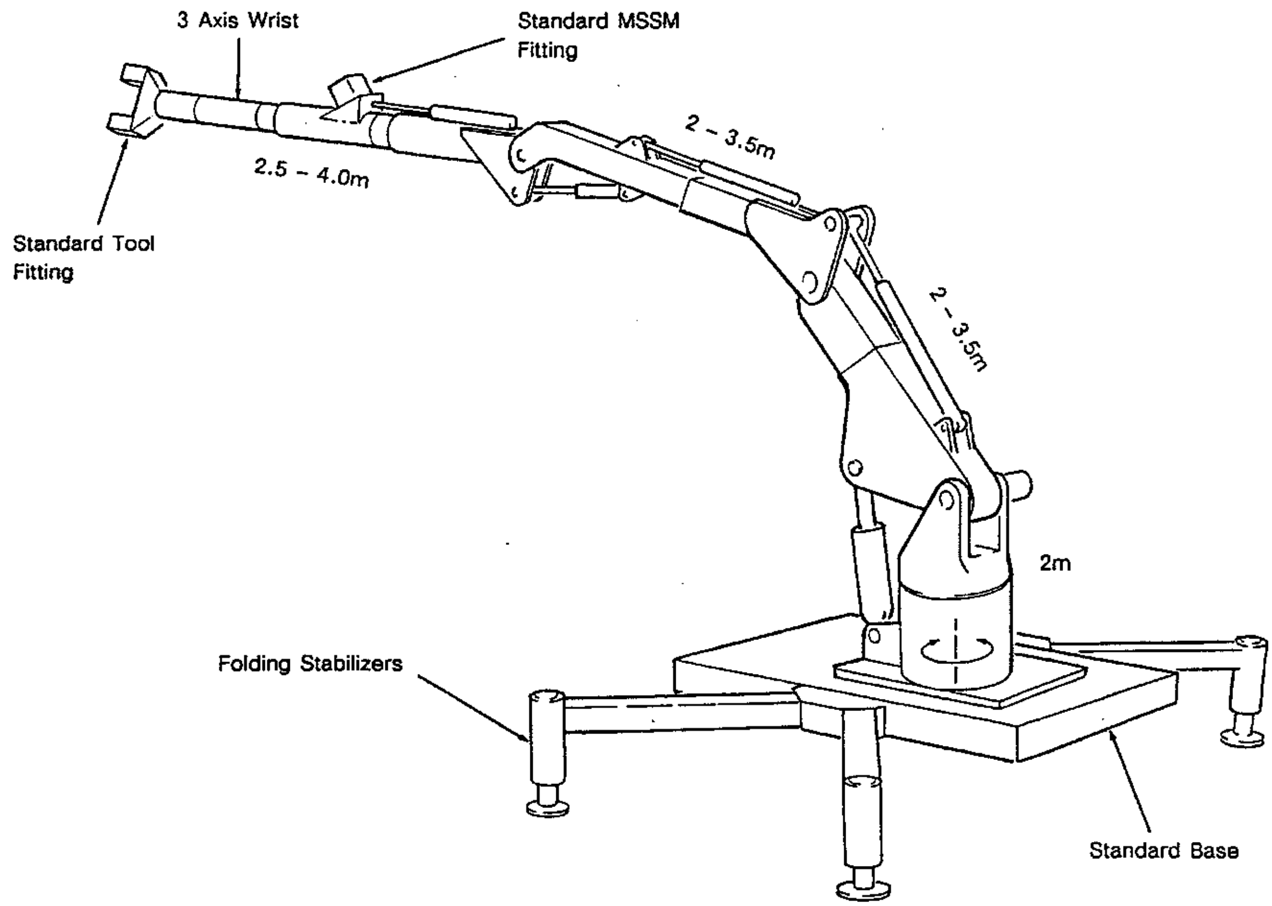


Figure 6.11-15. Mobile Heavy Duty Manipulator

The manipulator and transporter are electrically driven. Three modes of control are planned similar to the deployable heavy lift manipulator. The manipulator has a powered interface that accommodates a dexterous or power manipulator.

6.11.5.4 **Two-Armed Dexterous Manipulator** - The Mascot[5] two-armed "master-slave" dexterous manipulator is shown in Figure 6.11-16. It has an "elbows up" configuration with enhanced force reflection capability. It has a highly sensitive "force reflection" capability and allows the operator to experience a sense of "feel" when exerting a force or manipulating an object. The manipulator may be divided into two separate halves that form two individual arms.

The manipulator is a general purpose tool where the slave is positioned at the workplace by one of the aforementioned transporters. The identical master is located at a remote work station. Operator movements of the master cause corresponding movements of the slave. Each arm is able to handle loads up to 20 kg in any direction for 15 minutes and 12 kg in any direction indefinitely.

Each arm has six degrees of freedom, plus jaw gripper movement and shoulder indexing. In addition to the normal "master-slave" control, the fully digital control system allows "teach and repeat" modes of operation. It has advanced control features which allow force scaling and pre-trajectory planning.

During use, the operator may arrange the relationship between the master and slave so that there is a comfortable working position; i.e., if working overhead, the master-slave relationship may be offset by 90°. Similarly, the force reflecting ratio may be scaled so that the weight experienced by the operator is less than the object being manipulated. When carrying out a difficult remote operation such as drilling or welding, the manipulator may be commanded to traverse a straight line.

6.11.5.5 **Small Power Manipulator** - Figure 6.11-17 shows the RD500.[7] It is a single-armed force-reflecting manipulator with a relatively high load capacity of 50 kg. It has been designed to be rugged and reliable. The primary control system is a "master-slave," but it can function in automatic mode as a robot.

The small power manipulator will be used as a general purpose manipulator where the slave is normally positioned at the work place by a larger transporter. The manipulator is normally used as an individual tool with a set of gripper jaws. Where necessary, the manipulator can hold a standard tool or it can position a special device, such as a welding tool, to carry out a particular task.

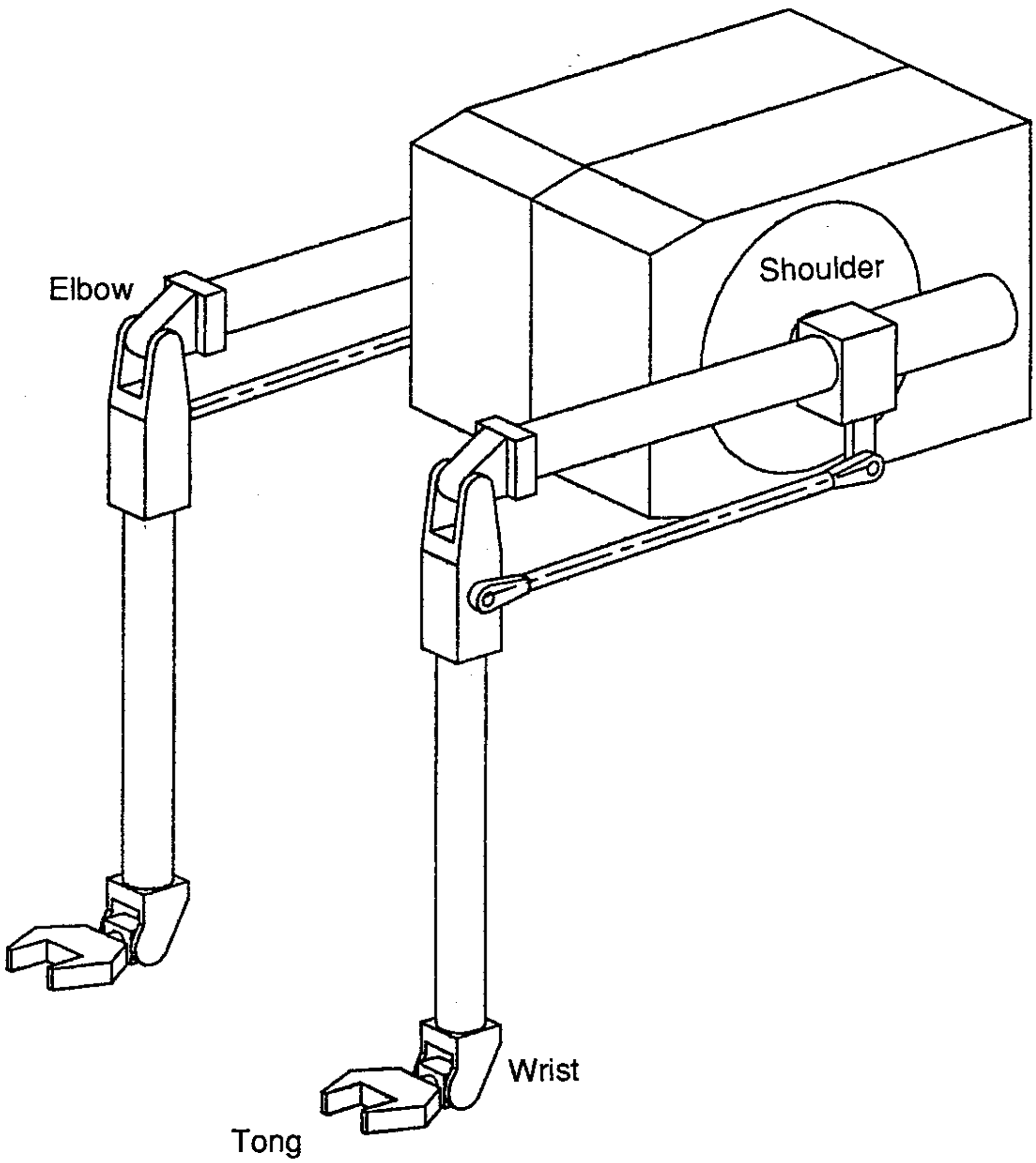


Figure 6.11-16. Two-Arm Dexterous Manipulator

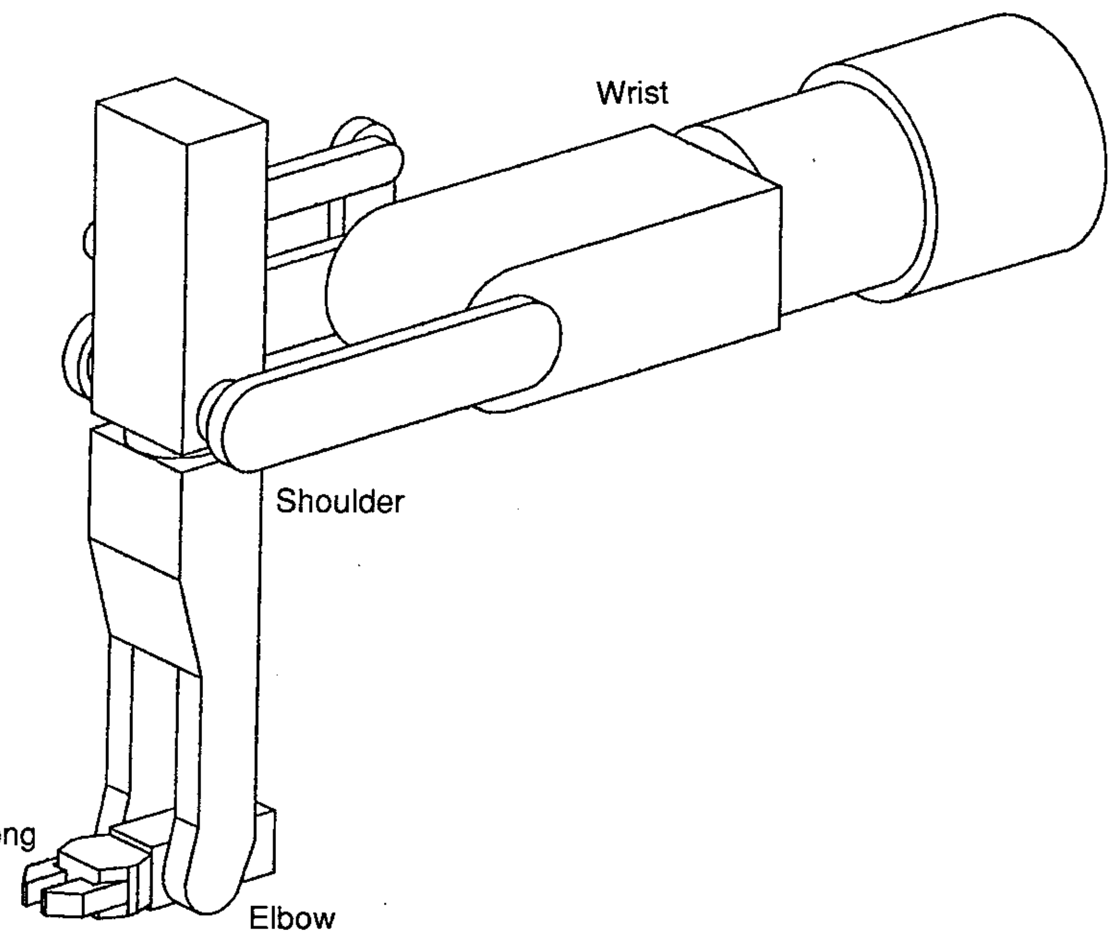


Figure 6.11-17. Small Power Manipulator

The arm can support a nominal payload of 50 kg for limited periods and 33 kg continuously. The arm has 6 degrees of freedom and is powered by electric motors through harmonic-drive gear boxes.

During operation, the manipulator can select force scaling ratios of 1:10 or 1:4 as required by the operator. It has a geometric scaling ratio of 1:1.5; i.e., 150 mm movement of the master provides 100 mm movement of the arm. This allows the operator to tackle delicate positioning operations with increased dexterity.

6.11.5.6 **Steam Generator Robot** - Figure 6.11-18 shows the overall arrangement of the steam generator robot. This robot may be used to inspect and repair heat exchanger tubes. The robot has four axes in a plane at right angles to the tube sheet. All four joints are coordinated to provide X, Y, and Z positioning of a tool mounted on the end of the robot arm.

Each joint is a self-contained module, complete with drive motor, gearbox, and position sensor. Basic joint modules are bolted together with different length links to configure the robot to the different heat exchanger units; i.e., the liquid lead/steam generator or helium/steam generator. To enhance radiation resistance, the joints contain no electronics with all feedback provided by resolvers. Maintenance and decontamination are enhanced by providing the joint modules with a means of disassembly.

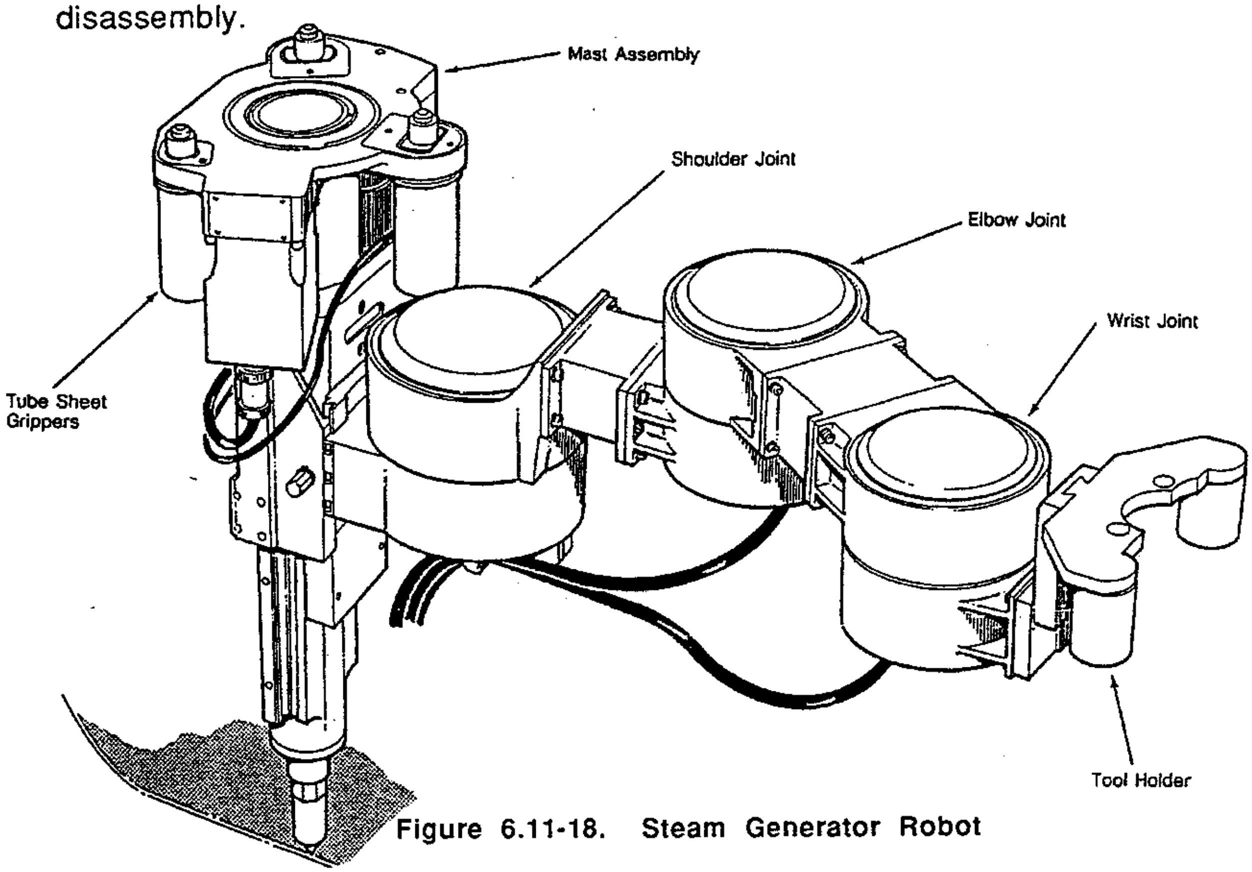


Figure 6.11-18. Steam Generator Robot

References for 6.11

1. In-vessel vehicular system produced by SPAR and Commissariat A L'Energie Atomique (CEA) under contract to NET

2. Lower Plug Manipulator portion of the Canadian ITER contribution produced by SPAR under contract to CFFTP

3. JET Remote Handling Equipment produced by JET team.

4. SPAR 2500 and Schilling manipulators in DOE sponsored Underground Storage Tank Technology Demonstration at Hanford

5. Mascot produced by ENEA (Italian Nuclear Agency)

6. X beam and STEM produced by Astro Aerospace

7. RD500 produced by CEA