REMOTE HANDLING AND MAINTENANCE OF FUSION REACTORS

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ABSTRACT

The operation of fusion reactors creates one of the most severe industrial environments for maintenance. Remote handling and maintenance systems are essential because of the high radiation levels. The severe temperatures and high heat fluxes incident on first wall equipment mean that maintenance and repair is required. The manipulator equipment must be compatible with vacuum, high temperatures and very high radiation fluxes. The equipment must enter through very small entry ports into the vacuum vessel and yet provide a rigid base for the manipulation of large components.

Spar has investigated these problems for the TFTR, JET and NET reactors. This paper describes design solutions appropriate to these toroidal reactors and discusses some of the difficulties associated with the implementation of these designs. Typical maintenance tasks are also described. Future fusion reactor maintenance equipment is considered.

INTRODUCTION

Major research efforts in Europe, Japan, the United States, and the Soviet Union are focusing on the possibility of using the huge reserves of energy unlocked by the fusion of hydrogen isotopes. The hope is that controlled fusion technology will provide a long term source of safe, cheap, and abundant energy.

The most successful fusion experiments to date have focused on the *tokamak* concept, originally developed in the Soviet Union in the 1960s. This consists of a high temperature low density plasma - of hydrogen, deuterium, or tritium nuclei and ions - contained within a toroidal vessel. A magnetic field confines the hot plasma (typically in excess of 100 million deg C) in order for fusion to occur and in order to isolate it from the internal structure of the containing vessel.

The application of remote handling technology in fusion research is centred on the difficulties of performing maintenance tasks within the containing vessel and of minimizing reactor downtime. The high temperatures generated within the reactor during operation necessitate the periodic inspection and replacement of reactor components in accordance with a rigorous predefined maintenance plan. Residual in-vessel heat and radiation levels dictate the need for complex but easy-to-use remotely controlled manipulators to carry out these tasks.

FUSION PROJECTS

To date, Spar RMSD has participated with CFFTP (Canadia Fusion Fuels Technology Project) in the design and development of remotely controlled maintenance manipulators for three major international fusion research projects.

The first is the United States experimental fusion reactor, TFTR (Tokamak Fusion Test Reactor) in Princeton, New Jersey, which has been operating since the end of 1982. The in-vessel manipulator for this project is currently being completed and manufactured by KfK (Kernforschungszentrum Karlsruhe) of West Germany.

The other two projects are European. JET (Joint European Torus), the largest fusion reactor built so far, is located near Oxford, England, and has been operating since mid-1983. At JET, an in-vessel maintenance manipulator has been built and is in use. With the benefit of practical experience, modifications and enhancements are now being made in order to improve the control and perception of in-vessel tasks by operators.

In pursuit of the European Community's commitment to the long-term development of fusion power, the design of an even larger tokamak reactor is under way at the Max-Planck-Institut fur Plasmaphysik in Munich, West Germany. NET (Next European Torus) is scheduled for its first day of operation in the mid-1990s. The conceptual design of an in-vessel maintenance manipulator for NET is currently being developed in parallel with the design of the reactor itself.

MAINTENANCE TASKS

Typical in-vessel maintenance tasks that require remote handling are:

(a) **Inspection of the first wall.** The *first wall* is a plasma-facing surface of protective tiles which is exposed to high radiation and heat fluxes during reactor operation. Closed-circuit television cameras, ultrasonic probes, and eddy current probes are examples of sensors used for inspection. Additionally, in TFTR, leak detection is performed within the evacuated containing vessel.

(b) **Removal, replacement, and repair of first wall tiles.** Periodically, over the life of a reactor, worn or damaged tiles have to be replaced. These weigh up to 40 kg, In some cases tiles may be repaired in situ using plasma spray techniques.

(c) **Removal and replacement of divertor plates.** The NET reactor design has a plasma shape which results in concentrated emissions of radiation and heat fluxes. Watercooled divertor plates, weighing as much as 1000 kg, are used in lieu of first wall tiles at these areas of concentrated heat flux. The high attrition of divertor plates necessitates their periodic removal and replacement.

(d) **Removal and replacement of in-vessel components.** Examples are stabilization coils, used during reactor operation to maintain the position of the plasma; sublimiters, protruding from the first wall to provide a physical limit to the plasma; and radio frequency heating antennae, used to heat the plasma.

DESIGN ISSUES

A summary of reactor characteristics and manipulator operating conditions is given in Table 1. It can be seen that all reactors are characterized by a constricted entry port providing access for a maintenance manipulator to the torus interior. The TFTR and NET manipulators operate under more extreme temperatures than that of JET. The TFTR manipulator is further distinguished by the need to operate under vacuum conditions, whereas the NET manipulator must function at extremely high radiation levels. NET is also a significantly larger reactor than the others, necessitating a manipulator of correspondingly greater reach.

From a functional point of view, the manipulator must perform the following in order to carry out the tasks described above:

(a) Transport payloads into and out of the torus;

(b) Provide a means of performing mobile or static inspection operations inside the torus;

(c) Locate and deploy dextrous end-effectors (for example, force-feedback servo-manipulators) or heavy payload end-effectors in any position around the torus interior.

(d) Provide a stable platform from which end-effectors and tools can perform maintenance tasks;

(e) Provide services (power, control links and cooling) to end-effectors, tools and, in some instances, payloads.

To date, these functional needs have been answered in all three projects by a manipulator consisting of a multi-jointed articulated cantilevered boom, capable in each case of servicing the entire reactor interior from a single entry port. Figure 1 shows the TFTR maintenance manipulator. A supporting control system provides the means of effecting full operator control which is simple to use. Critical areas and design drivers in this type of manipulator are:

(a) **Reach envelope.** The dimensions and proportions of the torus interior and the constricted entry port dictate the geometry and complexity of the manipulator. This results in the number of structural links; the number, type (roll, pitch, or yaw), and location of joints; and the angular range of motion of each joint. The geometry of the manipulator can also be affected by a desire to minimize the total number of joints in order to maximize end-point positioning accuracy, and by the need to minimize joint actuator torque requirements in order to ensure moderate joint sizes. The location of the entry port in all three reactors has been selected to allow a predominance of yaw joints whose drive torques are largely decoupled from gravitational loads.

(b) **Positioning accuracy.** The positioning accuracy of the manipulator is affected mainly by structural deflections and control system errors. The structural deflections are due to the manipulator's own weight and the weight of its payload. The joint control system errors are a function of joint backlash, joint stiction and friction effects, sensor accuracy and resolution, and actuator characteristics. Joint angle sensors are typically of 16-bit resolution. The actuators in the TFTR, JET, and NET manipulators are electric motors. The positional accuracy necessary to perform in-vessel maintenance tasks is achieved by a careful optimization of all these factors, and is of the order of 10 mm or less.

(c) **Operating conditions.** Critical environmental factors are vacuum, high temperature, and high radiation. Vacuum operation restricts the use of materials, in particular lubricants and other nonmetallics, to those with low outgassing and vacuum-stable properties. The lack of convective heat transfer leads to the oversizing of power dissipating components. A high temperature environment restricts the use of manipulator mounted electronic components, and requires careful design to allow for the differential expansion of dissimilar mechanical parts. It, like a vacuum environment, results in the oversizing of power dissipating components. High radiation dosage levels severely restrict the selection and life of electronic components (for example, television cameras) and sensors. In the case of the NET manipulator, the intense radiation level precludes the in-vessel use of semiconductors, and has restricted the selection of sensors to resolvers, limit switches, and other electro-mechanical devices. Where the use of electro-optical devices cannot be avoided, the design must accommodate their frequent replacement.

(d) **Safety and reliability.** Collisions between a maintenance manipulator - or its payload - and the reactor interior must be avoided to prevent damage to delicate and expensive equipment. Collision avoidance techniques include the use of proximity sensors, video feedback, and graphics simulation to alert an operator to an imminent problem. Failsafe operation is necessary in order to eliminate the need for direct human intervention and allow unmanned retrieval in the event of a manipulator failure. Reliable manipulator operation is highly desirable to avoid extensive periods of reactor downtime, assuring effective use of the large capital investment represented by research fusion reactors. Failsafe and reliable operation is ensured by rendering key components redundant, by oversizing vital electrical and mechanical parts, by employing self-checking control systems, and by the use of built-in test functions.

DESIGN SOLUTIONS

The TFTR maintenance manipulator is illustrated in Figure 1. A manipulator of similar configuration is in use at JET. Figures 2 to 5 show details of a concept design of the in-vessel maintenance manipulator for the NET fusion reactor.

EX-VESSEL MAINTENANCE

In addition to the maintenance of in-vessel components, equipment on the exterior of the reactor requires maintenance. Because of the radiation intensity at the exterior of the reactor, these maintenance activities must be performed remotely. Unlike in-vessel maintenance, ex-vessel maintenance does not present problems that have not been addressed in equipment designed for the nuclear industry. The main design feature of ex-vessel tokamak reactor manipulators is that of scale; manipulators with a reach of greater than 10 m are required to manoeuvre payloads in excess of several tonnes. Equipment has already been produced within the nuclear industry that can be applied to these tasks – see Figure 6. This equipment was designed and built by Spar RMSD for remote operations in Ontario Hydro's CANDU fission reactors. It has the following performance features:

Reach	8.5 m
Repeatability	1.0 mm
Payload	2.2 Tonnes

While the above may have to be scaled up to meet some of the larger fusion ex-vessel manipulator requirements, it is not believed to be a particularly difficult engineering problem to do so.

FUTURE FUSION REACTOR MAINTENANCE

Looking ahead to the requirements of operational fusion reactors leads to the conclusion that remote maintenance operations will be critical to cost-effective reactor performance. Although present first wall technology will undoubtedly be improved, high powered, long duration, controlled fusion burns and long operational life will certainly necessitate first wall repairs, maintenance, and inspection.

Production reactors conceived to date are in general considerably larger than existing research machine designs.

In order that the promise of cheap power from fusion may be realized, production fusion reactors will have to be operated with low system life cycle costs. Major refurbishments of reactors with lengthy downtimes will not be acceptable. Accordingly, in situ maintenance will be essential. A production reactor will have to incorporate specific design features that allow remote maintenance and repair. Maintenance operations will be time and safety critical in the sense that failures of the remote handling equipment must neither result in long periods of outage nor demand direct human intervention.

In summary, therefore, a production reactor maintenance manipulator will need the following features:

(a) Large scale and large payload capacity

(b) High accuracy

(c) High speed

(d) Failure tolerance

(e) High radiation resistance

(f) Ease of maintenance

ACKNOWLEDGEMENTS

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REFERENCES

(1) NET Status Report; Dec. 1985, NET Report 51

(2) NET In-Vessel Handling Unit Concept Design Report; CFFTP-P-86038, SPAR-R-1216, Apr.1987

(3) MUGUET, M., "Fusion Power and the JET Project"; JET, Abingdon, Oxon, Proc. Instn. Mech. Engrs. Vol. 199 No A4, 1985

(4) Tokamak Fusion Test Reactor Maintenance Manipulator Progress Review; Sept 1985, Princeton Plasma Physics Lab. TSD-R-49

(5) TFTR Maintenance Manipulator Final Design Review Minutes; KfK/PPL; Jul. 1986

Table 1: Summary of Fusion Reactor Characteristics Relevant to In-Vessel Maintenance

	TFTR	JET	NET
Reactor major radius to centre of vessel	2.6 m	3.0 m	5.2 m
Internal horizontal diameter	2.3 m	2.6 m	3.0 m
Internal vertical diameter	2.3 m	4.2 m	6.0 m
Entry port dimensions at most constricted point	0.8 m x 0.6 m	1.0 m x 0.5 m	2.0 m x 0.6 m
Entry port length	2.8 m	3.0 m	4.2 m
Temperature during maintenance operations	20–150 deg C	20–50 deg C	20–150 deg C
In–vessel atmosphere during maintenance operations	Vacuum or inert gas	Air at 15% relative humidity	Helium or Argon
Radiation level	100 rads/hr	200 rads/hr	3E6 rads/hr
Estimated total dosage for manipulator	1E5 rads	2E5 rads	3E10 rads
Maximum payload at full reach	225 kg	300 kg	1000 kg
Manipulator operational life	8 yrs	5 yrs	13 yrs

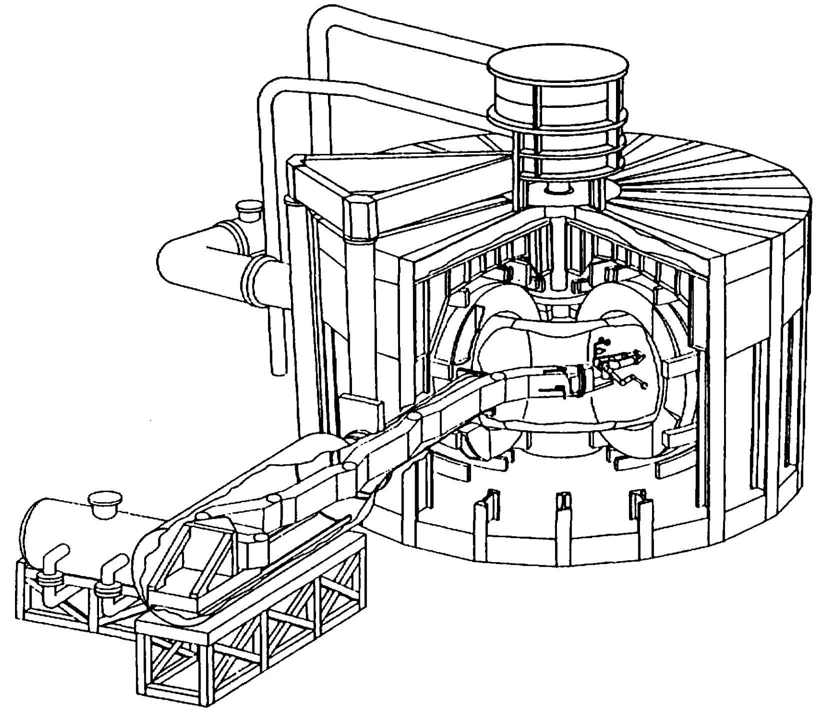

FIGURE 1- TFTR MAINTENANCE MANIPULATOR

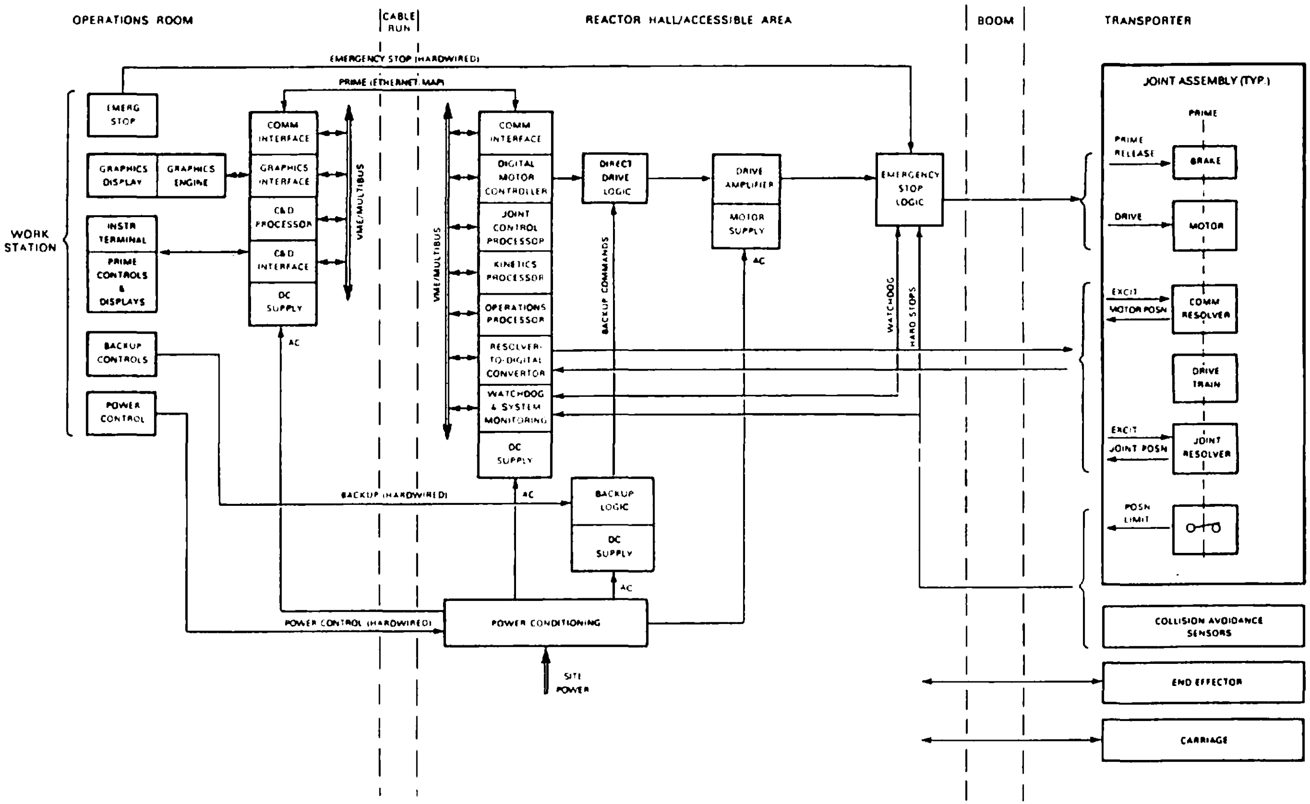

FIGURE 2- NET MANIPULATOR BLOCK DIAGRAM

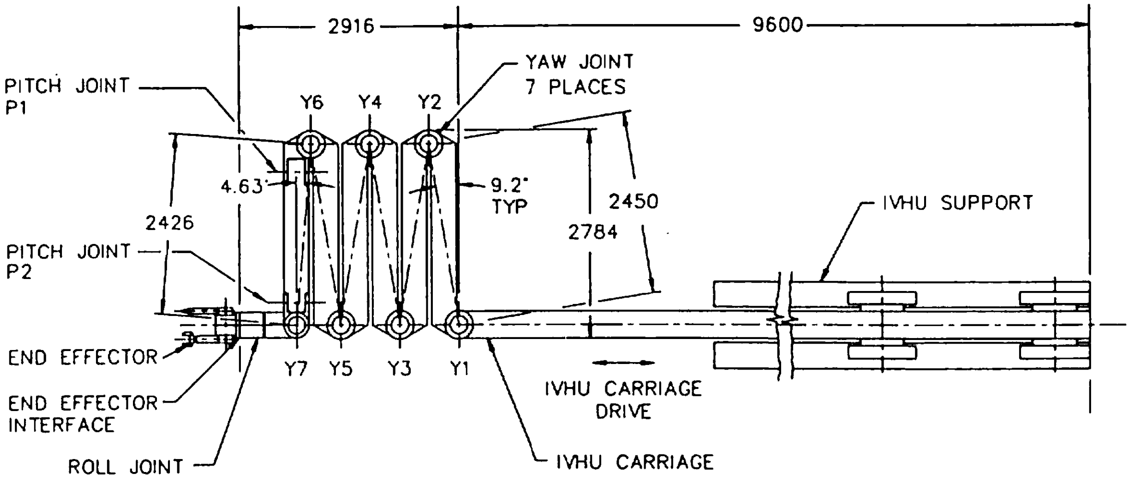

FIGURE 3- NET MANIPULATOR OVERALL DIMENSIONS

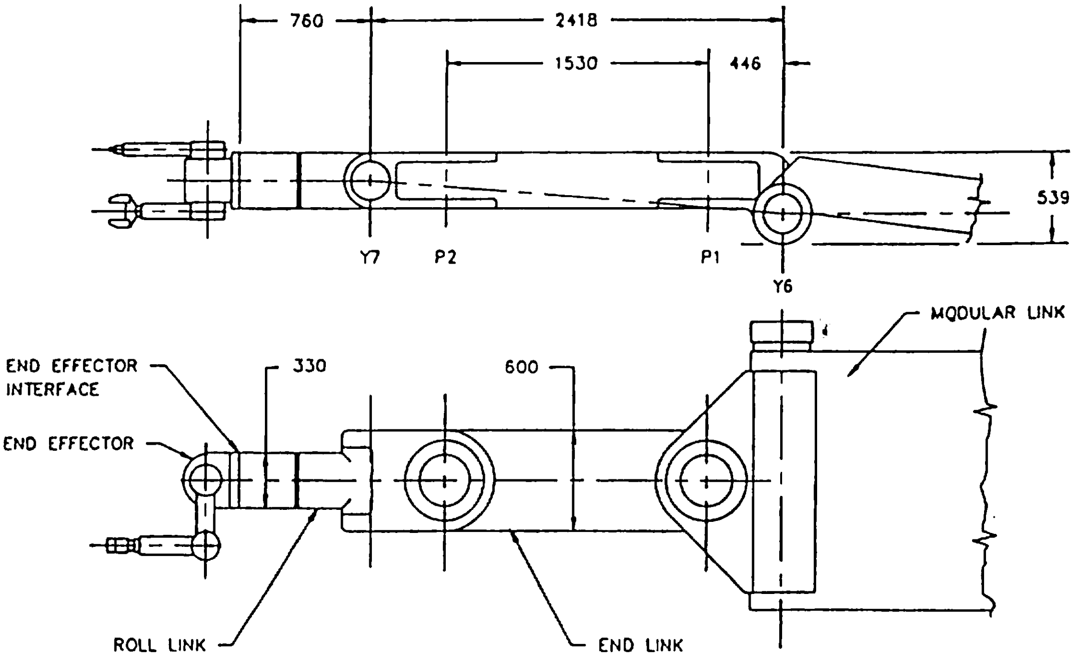

FIGURE 4- NET MANIPULATOR END LINK & ROLL UNIT

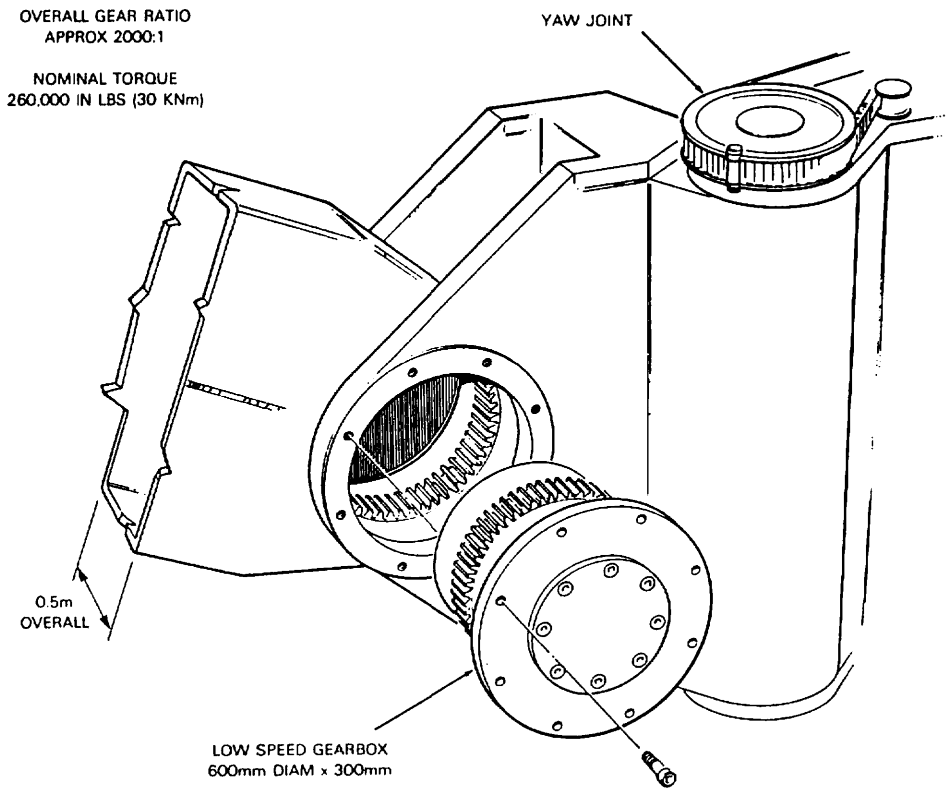

FIGURE 5- NET MANIPULATOR PITCH JOINT

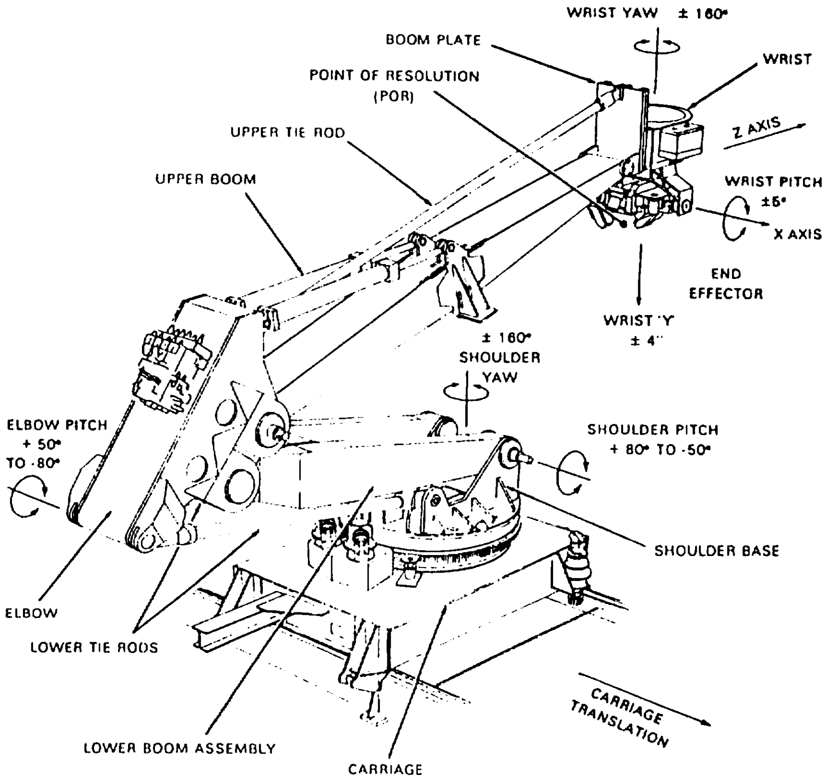

FIGURE 6- LARGE MANIPULATOR SUITABLE FOR EX-VESSEL OPERATIONS