

REMOTE MAINTENANCE FOR FUSION: REQUIREMENTS VS TECHNOLOGY GAP*

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Abstract

Today's remote handling technology was developed in response to the remote maintenance (RM) requirements of the fission community's nuclear fuel recycle process. The needs of the fusion community present new challenges to the remote handling experts of the world. New difficulties are superimposed on the difficulties experienced in maintaining fission processes. Today's technology must be enhanced to respond to the RM needs of these future huge investments. This paper first discusses the current RM needs for fusion based on existing facilities and designs of future machines. It then exposes the gap between these requirements and existing RM technology and recommends ways to extend the state of the art to close this gap.

Introduction

Remote maintenance technology has evolved progressively since its beginning in the 1940s for the nuclear power and weapons industries. This evolution has been driven by the application and, as such, is underdeveloped for other applications. This paper addresses the status of RM technology, outlines its deficiencies for fusion machines, and recommends technology growth to meet the needs of future fusion devices.

Historical Perspective

Today's remote handling technology has been developed over a 40-year period and is primarily the result of many years of development of systems to satisfy the requirements of the fission community's nuclear fuel cycle. Early systems took a simple approach, using an impact wrench suspended on the hook of an overhead bridge crane to manipulate coarse threaded fasteners and rugged components. Developments led to mechanical master-slave manipulators with much greater dexterity and sensitivity but very limited spatial coverage. Articulated power arms mounted on 3-axis positioning transporters were also developed. These allowed large volume coverage but had limited dexterity. Ultimately, the teleoperated servomanipulator system was pursued. This system attempted to retain the dexterity and sensitivity of the master-slave manipulators but with an overhead transporter that allowed the system to provide coverage of the entire facility. These teleoperators were high-performance devices with greatly improved capability, but they were also very expensive. The opposing needs for increased performance and lower cost have driven developers in different directions. Even so, multiple enhancements have been made in recent years to respond to these requirements. Also, teleoperators have been aggressively pursued for space and underwater applications.

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Despite the tremendous progress over the last four decades, RM systems still fall far short of human capabilities. Present teleoperator systems substantially impair an operator's sensory perception while attenuating his dexterity and sensitivity. The best systems available today provide work efficiency factors of 5:1 to 8:1; that is, it takes 5 to 8 times longer to complete a task with a teleoperator than it would to complete it manually. In general, the ratio increases with the difficulty of the task.

Throughout the evolution of RM technology, the inadequacies of the RM systems were compensated for in the design of the equipment to be maintained. Equipment was spaced to provide physical access for the RM package, which can be rather large. Maintenance tasks were kept as simple as possible, with remotely maintained components being overdesigned to resist the forces inadvertently applied by the RM system because of its lack of sensitivity. All of these factors led to large-volume remote facilities with components designed to allow easy access and tolerate physical abuse. As the performance of RM systems increased, especially that of systems with high-quality force reflection and good dexterity, facility size could be reduced since equipment could be arranged more efficiently, and the need for overdesign also decreased. This trend is continuing but has not progressed sufficiently to address the new and different requirements of fusion machines.

When one considers the mean time between failures (MTBF) of fusion machines such as TFTR, JET, and some of their predecessors and then superimposes the present-day remote manipulator work efficiency factors, the need for significantly improved systems becomes apparent. A utility that is contemplating the ownership of a fusion power plant will obviously study the projected machine availability very carefully. It becomes obvious that there is an extreme need to increase the MTBF of the machines and to drastically improve the remote handling capability.

Remote Maintenance Issues for Fusion Machines

Fusion machines pose many unique RM challenges not experienced in the fission community. Machine configurations have very limited flexibility, being dictated almost exclusively by the physics needs. Historically, the facility and equipment for a fission process were designed after the RM system was firmly established. The RM system within these facilities varied drastically - for instance, a crane/impact wrench system vs a servomanipulator system. In fusion machines, the type of RM system is not a variable. Rather, the RM system must be chosen (or developed) to meet a specific configuration. The machine requirements also typically result in very high equipment density, making accessibility by a set of mechanical arms very difficult. Again, the arrangement of fission devices was historically based on the manipulator chosen. Fusion devices do not allow this luxury. Finally, the components to be maintained tend to be much more fragile, relying on RM equipment sensitivity instead of component ruggedness.

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The electronics and sensors associated with many of the diagnostics make RM a very imposing task.

From an operational viewpoint, the RM requirements of fusion machines also make it necessary for manipulators to work in a vertically upward attitude inside the vessel when working on the upper diverters or underneath the machine when working on vertical diagnostics. The normal hardware and software of teleoperated manipulators will have to be revised to enable an operator to work the manipulators in this orientation without getting confused. The JET staff have developed a computer model of their in-vessel manipulator system with real-time animation. This model tracks the actual manipulators in real time. This is a major step in keeping the operator properly oriented with the real world.

Fission systems hardware is arranged to be serviced from above or from the side. The manipulator system is typically transported on a vertically oriented telescoping boom supported by an overhead bridge-trolley system. This arrangement does not fulfill the needs of a fusion machine, in which access to the area underneath the machine is necessary for maintaining diagnostics and other components penetrating the vessel. The JET maintenance system has a horizontal telescoping boom on the end of the vertical boom for these tasks. Others advocate a remotely controlled floor-mounted vehicle that is equipped with manipulators and cameras.

Remote maintenance within the vacuum vessel is to be carried out in similar ways at TFTR and JET. Manipulators supported on the end of a long horizontal articulated boom are moved into the vessel through a horizontal port and positioned at the work site. A lot of development money has been spent on this approach, but it is not yet a fully proven technology.

A significant issue that must be addressed by the fusion community is the gap in technical understanding between the designers of fusion equipment and the RM designers. In each discipline there is little understanding of the other. In the past, those responsible for designing a nuclear facility had a thorough understanding of the remote technology needs and accommodated these needs in the facility and equipment designs. This is not the case with the designers of fusion facilities. This gap must be closed by thorough interaction between these disciplines.

At the fundamental level, the fusion community must accept the need for RM as coequal with other machine requirements. There are examples of fusion devices that proceeded into the conceptual design phase while the RM issues of the machine components and, more specifically, the remote handling systems themselves were delayed. It was argued that remote handling systems from the fission community or other programs will fulfill the needs. These examples have shown this logic to be erroneous.

Fusion power cannot be commercialized without RM. An unrepairable failure of a major R&D fusion machine would have repercussions that cannot be tolerated. Support from the commercial sector and the federal sponsors, be it technical or monetary, would be in jeopardy. A significant failure of this type would prove almost as devastating as a failure in the basic machine. To avoid such a setback in the quest toward

a commercial reality, future machines must adequately address RM issues. Some basic lessons from the 40-year history of RM can be applied fruitfully.

First, it is necessary to supply a remote handling system that provides a capability. This includes the remotely operated cranes, manipulators, transporters, camera systems, etc. Second, components that are expected to require RM must be designed so that the maintenance functions to be performed are within the capabilities of that remote handling system. The second aspect generally turns out to be much more difficult to implement than the first. The RM requirements imposed on a piece of equipment must be treated just like any other requirement; they are no more important, but certainly no less important. Third, the design of the RM system must be integrated into the machine and the balance of plant from the start. The RM system will have more influence on the configuration of everything outside the machine than any other single aspect.

RM Technology Development

To meet the coming needs of fusion devices, RM technology must grow and improve. Today, no commercially available manipulator system in the United States can fulfill all of the requirements for an acceptable remote handling system for fusion machines. Each available system has one or more significant deficiencies or shortcomings that make it unacceptable. Just as for any other necessary component that is commercially unavailable, the technology must be developed. Remote handling components that fall into this category should be treated just like any other component requiring development.

Four generic areas of the technology will require development: transporters, manipulators, sensors, and obstacle avoidance.

A 3-axis transporter is necessary to locate the manipulator package wherever maintenance must be done. This package includes the slave manipulator arms, cameras, lights, and hoist. For a machine the size of ITER, or even larger future machines, this becomes a formidable task. This requirement dictates the development of transporters that have significantly more reach, stiffness, and dexterity than existing systems. The approach today is to use an articulated horizontal boom to position an in-vessel manipulator package and an overhead bridge-trolley-vertical boom to position an ex-vessel manipulator package. The longest booms now in use have a horizontal or vertical reach of approximately 35 ft. At significantly longer reaches, stability of the boom tip becomes a problem. Existing in-vessel articulated and telescoping booms have already experienced these difficulties.

Floor-mounted transporters that can carry a full manipulator package, particularly with the ability for the manipulators to work overhead, are also needed. Such a unit must be able to maneuver in a very congested environment. Umbilical cords necessary for power and control become a problem. The transporter must be small but must supply a stable base from which to operate the manipulators.

As stated earlier, no commercially available manipulator in the United States fulfills all of the requirements for maintenance of fusion machines. The

ideal slave manipulator package should emulate man's upper body in size, strength, dexterity, sensitivity, and sensory perception. In regard to the manipulator slave arms, several improvements need to be made. End effectors need much work, both to improve their dexterity and to provide tactile sensing. A three-fingered end effector would provide an added degree of capability for accomplishing relatively delicate tasks. The wrist mechanism needs a lot of attention. We must reduce the bulkiness, improve the dexterity, and solve the singularity problems. The arms need another degree of freedom to enable the operator to reach around an obstacle to perform a repair function. The upper arms and shoulder area need to be very compact to permit access into the confined areas that are characteristic of fusion machines.

An improved sensory system will help to solve the problem of manipulator/equipment collisions. Such systems are necessary to help the operator relate to the environment in which he is working. Vision is always difficult. Stereo TV helps to solve the lack of depth perception characteristic of 2-D TV but sacrifices a lot in resolution and long-term use. TV systems characteristically provide no peripheral vision. The multiple-camera systems (typically one belly camera, one on a right wing, and one on a left wing) used to overcome this lack are very difficult to operate in confined spaces.

Visual sensor development offers the most promise. Since these sensors are mandatory for teleoperation, they are already present as part of the manipulator package. Adding sensors could decrease reliability with the additional components and cabling. Advanced vision-based feedback such as image recognition, range finding, or interactivity with the graphics models would provide a powerful capability to manipulator systems and their control. This would greatly enhance the efficiency and reliability of remote operations while offering a transparent collision avoidance method.

The most advanced manipulators in the United States today that have a working capability of 20 to 30 kg have a force-feedback sensitivity of about 0.5 kg at the tong. The sensitivities at the wrist, elbow, and shoulder are progressively worse. The transporter booms have no feedback at all. With this type of configuration, working in very tight quarters with the limited visibility provided by TV cameras, one can very easily cause more damage than is being repaired. There are no feasible systems today that will protect the remote maintenance equipment from itself. Placing proximity sensors or feelers on all of the possible impact points on the manipulator package is very difficult. Creating a global computer model of the machine to the detail that would be necessary to permit access in high-density equipment areas does not appear to be feasible. Obstacles must be avoided in a transparent manner before RM systems reach the efficiency and availability needed for fusion facilities.

In order to accomplish such far reaching goals, the fusion community must support basic research and development of RM technology. Achievements of the fission industry are inadequate and the developments in other areas are not directly applicable to the fusion problems. In addition, commercial sources are not interested in funding R&D since the market is so small. Therefore, RM R&D must become an essential

component of the overall fusion program. If the generic areas mentioned above are pursued as aggressively as the confinement physics and the plasma impurities, then fusion can move positively forward to a commercial reality.

Summary

There are many challenges and opportunities in bringing remote handling technology to the level needed for fusion energy to become a viable source of power. These can be summarized into three main points that are of absolute necessity in achieving a remotely maintainable fusion machine.

1. For each aspect of the machine, treat the RM requirement as equal to every other requirement.
2. Integrate RM capability into the whole from the very start.
3. Regard the RM system as underdeveloped, requiring R&D just like all other areas that are pushing the state of the art.