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ABSTRACT

The development of custom-designed work systems for use in subsea and hazardous locations has resulted in International Submarine Engineering Ltd. (ISE) and Ocean Systems Engineering, Inc (OSE) developing manipulators and tooling respectively, that can be transferred to new projects. This paper describes the application and further advancement of this combined technology in the design of a manipulator and control system to aid in defueling a nuclear reactor.

INTRODUCTION

In 1979, Reactor Unit Two at the Three Mile Island nuclear power generating station was severely damaged. Defueling operations necessary to place the core in a known configuration and to ensure that remaining fuel volumes cannot support criticality have continued since that time. The defueling of the Lower Core Support assembly (LCSA), which will commence on completion of the core region defueling, may require deliberate, controlled cutting and removal of the structure, and debris breaking and transport.

The MANFRED (MANipulators For REactor Defueling) System is a remotely-operated, heavy duty, stainless steel manipulator system designed specifically to assist in the reactor defueling operations. In particular, the MANFRED System provides the capability to operate remotely a variety of custom-designed work tools which are used to gain access to areas within and below the LCSA. The manipulators are shown suspended over the LCSA in Figure 1.

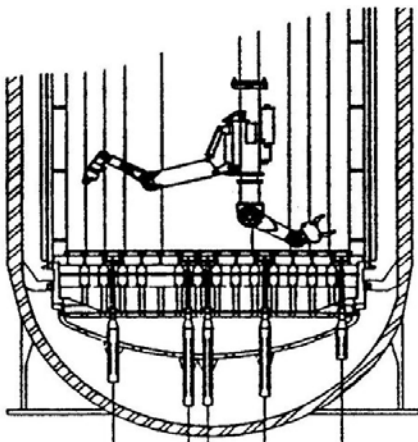


Figure 1 MANIPULATORS OVER LCSA

As in the subsea industry, operational requirements in a nuclear environment are met with the use of remotely controlled equipment and a minimum of manned intervention. Recently developed technology for the

HYDRA™ AT-1850 deep (1850 meters) ROV system which has evolved from previous deep ROV systems was transferred directly to the MANFRED project. Siemens (SMP) As microprocessor-based telemetry and control electronics (developed for this application by RMS Industrial Control of Port Coquitlam, BC), IBM PC-based graphics and high speed data links, and spatially-correspondent manipulator control algorithms formed the basis of the control subsystem design. The manipulator design, including the integration of the control subsystem to meet the contracted design requirements followed.

International Submarine Engineering Ltd. (ISE) a world leader in the application of robotic and remote control technologies in subsea and hostile environments, and Ocean Systems Engineering, Inc (OSE) a leader in subsea work system design and implementation, jointly bid and were awarded the MANFRED contract.

DESIGN REQUIREMENTS

Functional Requirements

The MANFRED System is designed to assist in the removal of core material from the LCSA and in gaining access through the LCSA to the lower head of the reactor vessel. In this role, the equipment is required to perform the following functions:

- Cut or break accumulations of fuel debris;
- Cut portions of the LCSA structure as required;
- Support structural pieces as they are cut loose, grasp and handle pieces of debris or pieces cut from the structure, and place the pieces in transfer containers;
- Clean adherent or loose fuel debris from the structural surfaces;
- Position tools to perform cutting, breaking, cleaning and handling operations;
- Provide visual inspection and monitoring capabilities for these and other operations; and
- Perform miscellaneous piece and tool-handling tasks.

Operational Requirements

Existing tools are used to support and deploy the MANFRED System. In particular, a Manual Tool Positioner (MTP), 18 ft long (extendable to 32.5 ft) and constructed of 8-inch diameter Sch.80 stainless steel pipe, serves as the mount for the manipulators. Equipment and tool changeout requirements are to be minimized to reduce non-productive labour.

The overall geometry of the manipulators is governed by the reactor vessel size, the flexibility required to place and operate the tools, and the need to stabilize the MTP. This stabilization requirement led to the dual-manipulator concept. The need to lift and handle 13-inch thick forging cut outs led to the specification of a 350 lb lift capacity and a 800 lb holding and carrying capacity.

The manipulators are to be operable from two separate console control stations, either directly from the Work Platform, which is situated on top of the reactor vessel or from the defueling Control Room which is located outside the containment building.

Duplication of all controls, safety interlocks and operator access to a stereo vision system and a real time colour graphics display formed the basis of the control console designs.

Environmental and Material Constraints

Equipment used to defuel the LCSA is designed to operate in the reactor vessel under 35 ft of borated water at temperature between 50 degrees F and 200 degrees F in radiation fields up to 5×10^3 R/hr to an integrated dose of 10^7 R.

Control equipment which operates in air will be exposed to radiation fields up to 50 mR/hr to an integrated dose of 10^3 R. The design temperature for components in air is 50 degrees F to 130 degrees F at a relative humidity of 10% to 100% and a pressure between 12.2 psia and 15.2 psia.

Beryllium or beryllium compounds are prohibited in any equipment to be located on the defueling platform or in the reactor vessel, as beryllium tends to promote the nuclear reactions.

Any chemicals, such as lubricants, solvents, sealants, and paints which could contaminate the reactor coolant or promote corrosion require chemical evaluation and approval before use.

Hydraulic Fluid

The hydraulic subsystem for operating the manipulators and tools is designed to use a hydraulic fluid compatible with the reactor coolant in case of leakage. A solution of water, borated to 5000 ppm with Polybor and a High Water Base Fluid (HWBF) additive at 5% concentration was chosen to eliminate organic content and provide some lubrication.

Two test programs were run on the hydraulic components using borated hydraulic fluid with and without the HWBF additive. Without the HWBF additive all servo system components and cylinders were found to have good service life, while rate valves, reducers and reliefs were found to stick. With the additive, the operational life of all components at an operating pressure of 2500 psi was acceptable.

General Description of the MANFRED System

The major components of the MANFRED System are as follows:

- i) a pair of manipulators - the Work Manipulator and the Grabber manipulator - mounted on the Manipulator Mounting Post. (see Figure 2);
- ii) a primary "Control Room Console" with two master controllers - a "Work master Controller" and a "Grabber master Controller." (see Figure 3);
- iii) a secondary "Work Platform Console" with two duplicate master controllers. (see Figure 4);
- iv) a Valve Rack;
- v) a Hydraulic Power Unit (HPU);
- vi) a Pan-and-Tilt Arrangement consisting of a stereo video camera pair, a colour video camera, two lights and a pan-and tilt unit;

- vii) a set of tools, each which can be held in the latch jaws of the Work Manipulator.

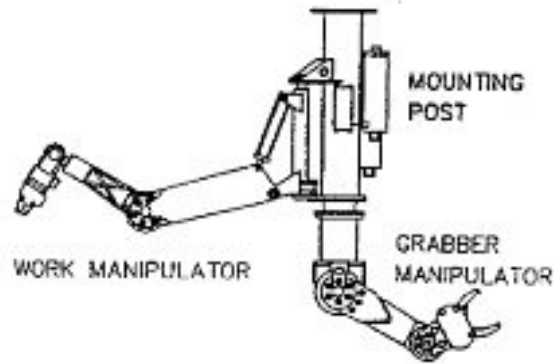


Figure 2 MANFRED MANIPULATORS

Manipulator Mounting Post

The Manipulator Mounting Post which is fastened to the bottom of the MTP to deploy the two manipulators in the reactor vessel, serves as the mounting pint for the Work and Grabber manipulators. Two junction cans, two servo valve packs, and two set of check valves are also mounted on the post. The two junction cans are for the feedback wiring and optional force sensing equipment of each manipulator.

Hydraulic Subsystem

The Hydraulic subsystem consists of the Hydraulic Power Unit (HPU), the Valve Rack and the hydraulic equipment attached to the mounting post.

The HPU provides hydraulic fluid (Borated water) at an operating pressure of 2200 to 2500 psi to a maximum flow rate of 20 gpm.

The Valve Rack provides mounting areas for pressure reducing valves, a Tool Manifold, and the Main and Auxiliary Rate packs. The pressure reducing valves limit the hydraulic pressure to the two servo packs, the Main Rate Pack, and the Auxiliary Rate pack. The main Rate pack is used to operate the rate functions of the manipulators, e.g. jaw Open/Close. The Tool manifold which is pilot-operated from the Auxiliary Rate Pack, directory operates the tools.

The two servo valve packs mounted on the manipulator mounting Post provide hydraulic power to the actuators of the two manipulators. The Work Servo Pack contains six jet-pipe servo valves and the Grabber Servo pack contains three of these valves. Each servo pack also contains a poppet valve which is used to hydraulically lock the manipulator in position through pilot-operated check valves on the manipulator Mounting Post.

Electric Power Subsystem

The Electric Power Subsystem consists of two power distribution units (PDU's), the Electrical Distribution Box, and the electric power cables.

The PDU's which are mounted on the sides of the Work Platform Console, control the two electric motors (three-

phase) in the HPU, provide power for the contactors, multiple voltages for the video lights, and power for the rate valves.

The Electrical Distribution Box is mounted on the back of the Valve Rack. It is the junction box for the cables from the Work Platform Console, the Valve Rack, the manipulator Mounting Post, and the Pan-and-Tilt Arrangement. A Gas Compensation system is attached to the Electrical distribution Box which delivers Nitrogen gas through control cables to the junction cans to pressure compensate the submerged electronic equipment.

Control and Telemetry Subsystems

The Control and Telemetry subsystem consists of the control consoles, most importantly the telemetry electronics unit in each console, and the signal cables in the MANFRED System. A significant feature of this subsystem is the graphics computer and software.

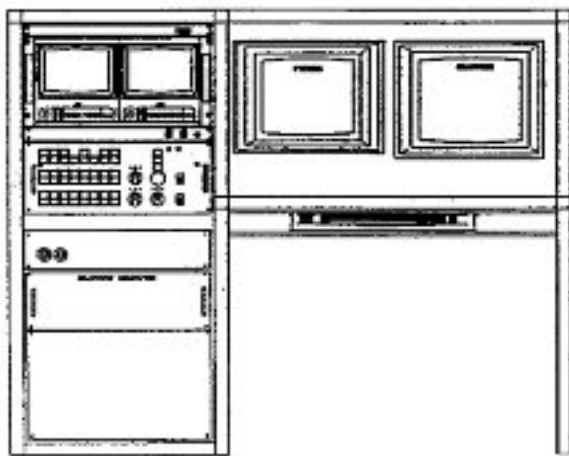


Figure 3 CONTROL ROOM CONSOLE

Control Consoles: The general arrangements of the MANFRED control consoles are shown in Figure 3 and Figure 4. Only one console can be in control of the system during operation. If the "MASTER" control keys on the two consoles are not in agreement, or if both are turned to the "DISABLE" position, the system is disabled.

Telemetry Electronics Units: The telemetry electronics units installed in the telemetry tray of each console contain Siemens CPU boards which use Intel 80188 microprocessors. The SMP board system executes application software on Kadaks's AMX Operating System. The telemetry units are connected by an RS485 half duplex, pulse code modulated data link. The data transmission rate is 125,000 bits per second, with an update rate of 25 times per second.

The telemetry electronics units consist primarily of Siemens SMP Eurocard format electronic components and custom-designed electronics boards, termination boards, and flexible connectors which are integrated with the SMP components. A specially-designed colour video overlay board integrated with the telemetry electronics allows text and graphics to be superimposed over a camera video signal.

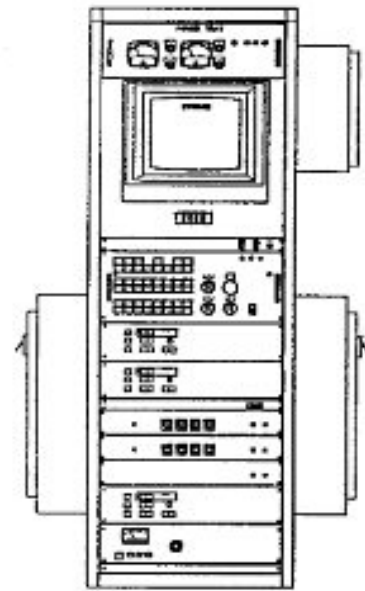


Figure 4 WORK PLATFORM CONSOLE

Graphics Computer: The IBM graphics computer and keyboard located in the Control Room Console allows and operator to select programmed telemetry or graphics software features which aid in settling up or in monitoring this operation of the MANFRED system

The IBM PC inputs data from the telemetry stream via a high-speed data link and maintains a database of all data in the telemetry stream. This data is used to create various graphics displays and is also monitored for alarm conditions. The main graphics display is a perspective view of the two manipulators and the LCSA. The operator can choose various viewpoints for the display, which is useful in providing an overall view of the manipulators, as opposed to the detailed views available from the video cameras. The graphics representation of the manipulator members also change colour when the manipulator joint positions differ from their setpoints, which indicates that the arm has hit something, stopping that particular joint from moving.

The IBM PC also has a low-speed link to the Control Room Telemetry Computer which is used in setting up the system and in playing back a teach sequence (see manipulator Control Method). All analog input and output signals have software scale and bias values which can be set or altered using the PC's keyboard. Also changeable from the keyboard are the manipulator PID control loop settings.

Manipulator Control Method: Two methods of manipulator control are available: Normal and Tech/Playback. Using the "Normal" control method, a master controller at the console in control is used to operate the corresponding manipulator directly. The Work Manipulator can also be operated in a "Teach" sequence, during which the setpoint positions are sampled and stored in the graphics computer's memory, and in a "Playback" sequence, during which the stored setpoint positions are used to repeat the "Teach" sequence automatically with the Work Manipulator.

The position signals which are used to provide spatially-correspondent control are "setpoint" signals, "feedback" signals, and "servo output" signals.

A Proportional-Integral-Derivative (PID) control loop is implemented in the SMP software which compares the error between the 'setpoint' signals from the joint position sensors on the master controller to the "feedback" signals from the joint position sensors on the corresponding manipulator. The resulting signals, which depend on the proportional error, the rate of change of the error, the steady-state error, and the programmed gains are "servo output" signals to the servo valves.

Video Subsystem

A stereo video camera pair, a colour camera, and two lights are mounted on a pan-and-tilt unit to form the "Pan-and-Tilt Arrangement." The stereo camera assembly mounted on the pan-and-tilt unit part of the 3 VISION Stereoscopic Video Camera System developed and produced by Stereoscopic Inc. Stereo vision is achieved by synchronizing left and right cameras at 120 Hz with liquid crystal shutters mounted in visors. Viewing a monitor modified to run at 120 Hz vertical scan frequency through the visors allows multiple observers to observe a stereo image without flicker.

Manipulator Subsystem

The Manipulator Subsystem consists of the master controllers for the Work and Grabber manipulators as well as these two "slave" manipulators.

Both the Work Manipulator and the Grabber Manipulator are the spatially-correspondent (SC) type. The Work Manipulator is operated using a 6SC master controller (one at each console location) and the Grabber manipulator is operated using a 3SC master controller (one at each console location).

Master Controllers: The master controller for the Work Manipulator has six SC functions (Swing, Shoulder, Elbow, Wrist Roll, Wrist Pitch and Wrist Yaw), one rate function (Jaws Latch, Unlatch), and a manipulator (Lock/Unlock) function.

The master controller for the Grabber Manipulator has three SC function (Swing, Shoulder, and Wrist), one rate function (Jaws Open/Close), and a manipulator Lock/Unlock function. The Grabber Master Controller also has three control switches for the camera pan-and-tilt unit (Pan left, Tilt Up/Down, and Pan Right) mounted on the handle.

Work Manipulator: The Work Manipulator is shown in Figure 5. It is an assembly of five members: the Vertical Column, the Upper Arm, the Forearm, the Wrist, and the Latch Jaws. Alternatively, the Work Manipulator may be described in terms of its six Sc functions or joints (Swing, Shoulder, Elbow, Wrist Roll, Wrist Pitch, and Wrist Yaw), and one rate function (Jaws Latch/Unlatch).

The "Swing" and "Shoulder" joints rotate 90 degrees and are positioned by 2.5-inch diameter, 2500 psi cylinders with carbon fibre barrels.

The Latch jaws are actuated by an integral "cylinder" in the jaw block. The Elbow and three wrist functions -- Wrist

Roll, Wrist Pitch, and Wrist Yaw-- are actuated by rotary actuators each with 180 degrees rotation.

Other specifications of the Work Manipulator are as follows:

- Structure: 316 & 17-4 PH SS
- Reach: 70 inches horizontal
- Lift at Full Extension: 350 lbs
- Weight in Air: 500 lbs
- Jaw Clamp Force: 1100 lbs @ tips

The Work Manipulator may be hydraulically "locked" and "unlocked" by using the Lock/Unlock switch on the handle of the Work Master Controller to close and open the poppet valve in the Work Manipulator Servo pack.

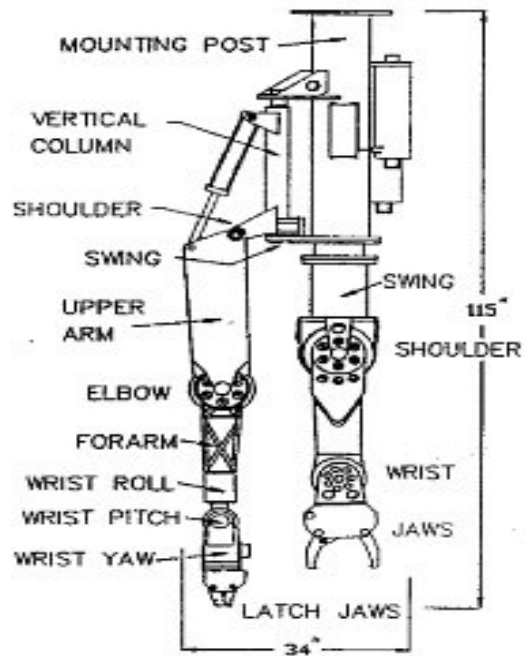


Figure 5 MANIPULATOR SUBSYSTEM

Grabber Manipulator: The Grabber Manipulator is also shown in Figure 5. It consists of four subassemblies: the Mounting Subassembly, the Arm and Shoulder Subassembly, the Wrist, and the Jaws. Alternatively, the Grabber manipulator may be described in terms of its three SC function or joints (Grabber Swing, Grabber Shoulder, and Grabber Wrist), and one rate function (Jaws Open/Close).

The "Swing", "Shoulder" and "Wrist" joints are rotary actuators. The Wrist and Shoulder joints each have 180 degrees rotation and the swing joint has 320 degrees rotation capability. The Grabber jaws are actuated by a 2.5-inch diameter, 1500 psi cylinder. Other specifications of the Grabber manipulator are as follows:

- Structure: 316 & 17-4 PH SS
- Reach: 40 inches horizontal
- Lift at Full Extension: 350 lbs

- Maximum Lift: 800 lbs
- Weight in Air: 420 lbs
- Jaw Clamp Force: 800 lbs @ tips.

The Grabber Manipulator may be “locked’ and “unlocked” by using the Lock/Unlock switch on the handle of the Grabber Master Controller to close and open the poppet valve in the Grabber Manipulator Servo Pack.

Tools

Most of the tools in the MANFRED system are hydraulically driven and are designed by Ocean Systems Engineering for deployment in the Latch jaws of the Work Manipulator. The tools are listed below:

- Universal Tool Holder
- Abrasive Cutoff Wheel
- Rotary Scaler
- Chipping Hammer
- Vertical Mill
- High Pressure Water Wash Nozzles
- Abrasive Cutoff jet
- Toolhead Holder
- Trash Bin
- Heavy-Duty Lifting Jaws

Universal Tool Holder: The Universal Tool Holder is designed to lower and raise the various tools to the Work Manipulator. Four of the larger tools, such as the Abrasive cut-off wheel are designed to hang from the Universal Tool Holder and can be lowered into place with minimal intervention by the Work Manipulator. The chipping hammer and Water Wash Nozzles are lowered into the water with the tool holder, then handled by the Work Manipulator.

Abrasive Cut-off Wheel: The abrasive Cut-off Wheel is designed to cut through vertical stand-offs supporting horizontal structural plates, and other support tubes. The cut-off wheel is designed to cut in a horizontal plane when it is held in position by the Universal Tool Holder and the Work Manipulator.

Rotary Scaler: The Rotary Scaler is used to clean deposited material from various surfaces, especially circular bore-holes. Several toolheads are available for use depending on the strength of adhesion between the deposited material and the surface. A triple-stacked wire brush, a spring-loaded star-wheel scaler and a three-inch wire brush are provided.

Vertical Mill Assembly: The Vertical Mill Assembly is used to remove adherent material from vertical surfaces. The tool design permits cleaning to substantially bare metal to provide a conductive path for plasma arc cutting tools.

Chipping Hammer: the chipping Hammer is used to break apart of chip off material adhering to various surfaces. The toolhead is vibrated by a hydraulic motor through a cam and spring arrangement. The tool is held by the Work

Manipulator but the shock of the blows is taken up by the shock mitigation sleeve and the tool’s weight.

High Pressure Water Wash Nozzles: Four water wash nozzle assemblies are provided which use a high pressure water jet from a nozzle to clean a surface of moderately adherent material and wash the material to a more convenient location for pickup. Each nozzle assembly can be held in the Latch Jaws of the Work Manipulator.

Abrasive Cut-Off Jet: The Abrasive Cut-off Jet cuts by using an abrasive material, such as garnet, introduced into a high velocity water stream. The jet with the entrapped abrasive material must move slowly to allow the abrasive to impinge on the material and carry it away. The cut is narrow and clean.

Tool Head Holder and Trash Bin: The various toolheads which become worn with use must be removed below the water surface and disposed of in a canister. The toolhead holder is designed to take replacement toolheads to the working tool. The trash bin is designed to contain or catch the toolhead after it has been used.

Heavy Duty Lifting Jaws: The heavy Duty Lifting Jaws Assembly has a large jaw opening and a large clamping force. It is designed to be carried by a T-Handle or a D-ring in the Work Manipulator’s Latch jaws. After clamping the Lifting Jaws to an object, the Work Manipulator can move the object from location to another.

CONCLUSION

The total project time from the initial design of the MANFRED system to its arrival at Three Mile Island was 6 months. It is presently fitted in a test stand at Three Mile Island for operator training and development of operational procedures. The MANFRED system illustrates the successful and rapid transfer of remote work system technology from the subsea industry to a hazard materials handling application.