THE BRIDGE BETWEEN MASTER AND SLAVE

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ABSTRACT

Remote manipulator operations require a high level of telepresence. This can be achieved by a combination of tactile audio and visual links used in association with an effective deployment system for the slave arms. The combination of these elements has been termed the 'bridge between master and slave' by the author. Each component is reviewed in the context of remote underwater and nuclear operations with the conclusion that certain cost-effective enhancements can be made to the ways in which we acquire sensibility to the remote environment and in which we view the mechanical design of more complex deployment systems.

1. Introduction

Remote intervention is common place in nuclear and underwater operations and a wide variety of tongs and manual manipulator systems are available for the former whilst relatively simple single speed hydraulically powered arms are in use subsea. Occasionally one finds manipulative systems where toxic chemicals are handled and similarly, such devices appear in sewers or complex structures. True powered master-slave manipulator systems are, surprisingly, relatively rare both in nuclear and underwater applications though, by virtue of increasing demand being placed on production rates offshore, more master-slave systems have found their way into that field than the nuclear which, in contrast, boasts systems of greater sophistication and development particularly in the field of tactile telepresence. Both sides enjoy improvements in the design of camera viewing systems, the nuclear industry being somewhat limited by the susceptibility of CCD based equipment to high radiation levels. Inasmuch as sound is concerned, only a few operations have bothered to investigate its usefulness. The deployment system for the manipulator arms, apart from the submersible in underwater operations is designed on an ad hoc basis using conventional engineering principles yet is expected to deploy the slave arm faithfully in quite controlled positions.

2. Historical Perspective - Remote Manipulator Systems

In the offshore industry, much effective work has been carried out in the past, more as a tribute to the skill of the operator than to any technical excellence of the equipment he is using, the which would have caused raised eyebrows in the nuclear industry. Success is still achieved with fixed speed hydraulic manipulators and it is of interest to note that the most popular constant speed arm was one containing its own built-in telescope - either on the shoulder or on the forearm. The single speed anthropomorphic geometry now commonplace on master slave systems - was much less popular requiring substantial mental gymnastics to move the end effector in a straight line, while being constrained by the polar motions of fixed length ligaments which have to be summed in one's head. Now variable rates, particularly those associated with servo systems enable such linking to take place without the operator having to think about it. Whether resolved motion controllers or genuine master arms are used, the operator is able to control his manipulator (slave) with reasonable telepresence even though force reflection may be absent from the system.

In the nuclear industry, most in-cave operations have been conducted using master-slave manipulators - MSM's, of the form shown in Figure 1

It is interesting to observe that although these are installed in pairs working through a wall above a bromide shielded window which gives excellent visibility, the operator often uses only one arm - but with two hands. More significant is his tendency to use two hands on a resolved motion master controller for a powered slave manipulator. There is little doubt that the standard MSM lacks telepresence in spite of its mechanical linking and excellent viewing conditions and this can be attributed to the inertia of the system rather than any real deficiencies in its balancing.

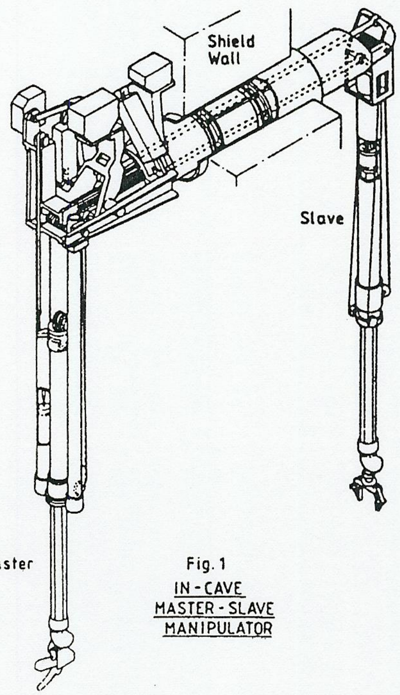


Fig. 1
IN-CAVE MASTER-SLAVE MANIPULATOR

From observation of operations in both the offshore and nuclear industry, two arms (left and right) are not used fully because, in the main, the control systems are not sufficiently 'transparent' to allow the operator to use the slave arms as if they were his own.

In more advanced systems e.g. Mascot IV and the new CERN manipulators, transparency and tactile telepresence is sufficiently developed to enable the operator to act with confidence using both arms whilst assisted by relatively modest viewing facilities. This results in the accomplishment of quite demanding manipulative tasks.

Occasionally, it is necessary to trade off the advantages offered by these arms where space restrictions do not permit their use or where superhuman lifting capacity is required (the above systems have a capacity of only 20 Kg). Similarly, continuous wrist rotation is sometimes called for but all these deviations are probably outside the true sphere of meaning of the phrases master-slave or telepresence.

3. Telepresence - Sound and Vision

The human body is attributed with five senses - sight, smell, taste, touch and hearing. True telepresence provides all five but it is doubtful whether there is any merit in considering taste and smell! Touch has been dealt with in the preceding section and in more detail by Vertut [1] and others.

3.1 Audio - Telepresence

The state of the art on most remote operations - leaving aside tactile sensing - is that they are often carried out using poor vision and no sound whatsoever. Good quality vision costs money but sound is a sense so easily translated that it is amazing that few operations are accompanied by audio monitoring of the remote activity. Microphones can enable the operator to know what his machine, particularly the deployment system, is doing and he is able to judge load, speed and even extent of travel, all from what he hears. Additionally, it is very easy to locate objects which have dropped by recalling the sound made as they fall. With two microphones, it is possible to work out where a can may have fallen just from the noise it makes. The CERN remote operations team have been working this way for many years.

A similar system has been installed on the Remote Handling Machine RHM, being built for the dismantling of one of the Pile Chimneys on the British Nuclear Fuels Sellafield site. In this it is anticipated that operators will be able to monitor the machine and also listen for the sound of chicken mesh and fibreglass as it is cut away and dropped down to a lower level.

3.2 Remote Vision

'Tele-vision' is a much more popular topic than 'tele-sound', and substantially more expensive to provide. Both colour and black and white cameras are available in mono and stereo form. Experience has shown that the most expensive system does not always produce the best results. Stereo cameras greatly improve work rates where perspective is essential but, because of convergence, they have a narrow field of vision and do not give a good impression of one's surroundings and tend to cause operator fatigue because of this. A useful provision, therefore, is the facility to switch from stereo to mono in order to reduce fatigue.

Apart from the viewing system, per se, its positioning is very important. In a master-slave system, it is desirable that the viewing line through the operator, master controller and monitor should be on the same axis as the line through the camera and slave arms [2]. This feature has been instituted in an unusual way on the remote handling system for the Pile Chimney dismantling project. Here, as a result of space limitations, two cameras with pan and tilt have been mounted on telescopic booms reaching down into the work site and to either side of the RHM which is equipped with two slave arms. The left hand camera monitors the left arm and vice versa. As one switches from left camera to right, it is possible to swivel the master controllers about a vertical axis to cause it to present them in line, in front of the main viewing monitor such that if viewed from the right hand side, the right manipulator controller is to the fore and the right manipulator arm is in camera view.

At CERN, all round viewing has been considered a priority and remote operations are monitored by units known as 'Private Eyes' which can position a camera almost anywhere in space offering a close up of the work or full vision of the broader environment. This technique derives a bonus which can be overlooked: the use of several cameras having a fairly large depth of field enables the operator to subconsciously build up a memory map of the room in which the manipulators are working. From this he is able to sense where he is at all times without actually having to stop and fix his position. It is felt that some effort spent in deriving video stills of the surroundings using a similar device to that found in departmental stores to look for shoplifters, would be of great benefit in establishing the bridge between the master and slave in the field of remote vision.

4. Remote Manipulator Support Systems

The final part of the bridge between master and slave is the physical support provided to the slave arms. In underwater operations this would be a submersible whilst in the nuclear industry it would be a mobile vehicle or crane carrying some form of articulated boom which can reach into the worksite with the slave arms carrying some form of toolrack and/or hoist. Regardless of its configuration, it must provide a stable and predictable base for the manipulators.

4.1 Underwater Manipulator Support Systems

In Underwater operations, particularly those carried out in mid-water, the extension of the slave arm puts an imbalancing force on the submersible which tends to cause the end effector to miss its target. It is, therefore, necessary to provide a clamping feature in the form of a grabber or suction cup which, when engaged with an underwater structure can resist current and wave motion as well as that induced by slave arm motion. Underwater vehicles enjoy considerable freedom of movement and access without anything more than the inconvenience of a trailing umbilical. Additionally, because of the relative insensitivity of the environment to oil leaks, the system designer is able to avail himself of the high power to weight ratio offered by hydraulics. Thus most conventional engineering operations can be carried out by a submersible equipped with a master-slave manipulator.

4.2 Deployment Systems for Planned Manipulator Intervention

It is axiomatic that a remote manipulator system will be designed around the geometric and environmental parameters of the equipment it is to maintain. Typical of this is the Articulated Boom for the JET Fusion Research apparatus at the Culham Laboratory. Figures 2a and 2b show the configuration of the boom which is required to circumvent the inner diameter of the toroidal vessel and which is powered by a system which cannot contaminate the interior of the vessel.

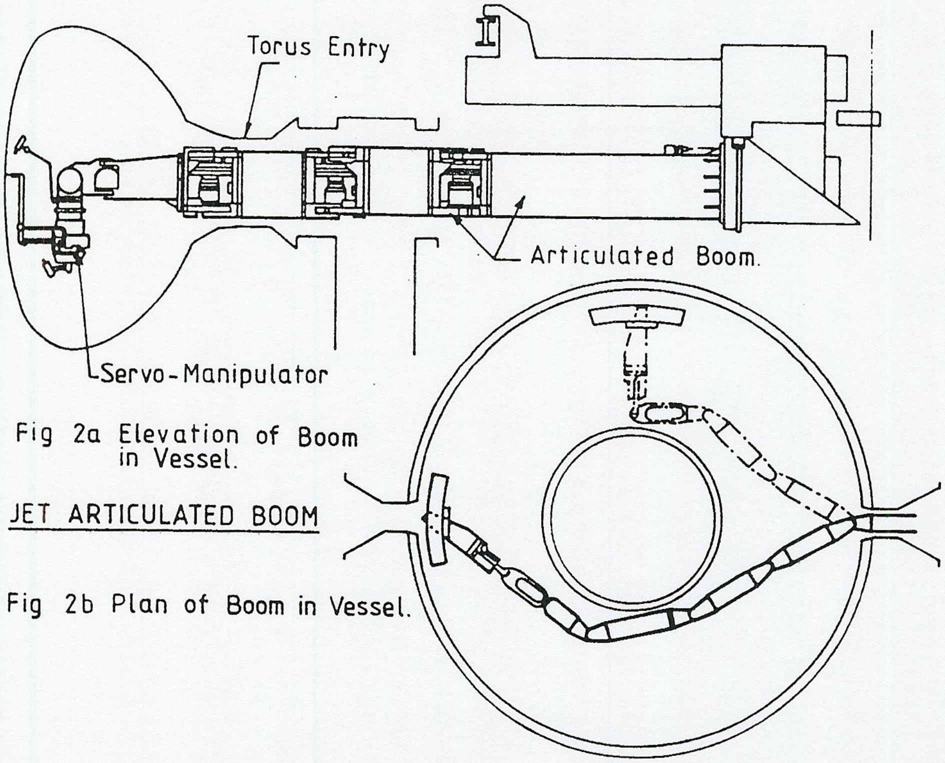


Fig 2a Elevation of Boom in Vessel.

JET ARTICULATED BOOM

Fig 2b Plan of Boom in Vessel.

The arm can be used either to deploy a master slave manipulator system, Mascot IV, or an end effector capable of positioning a heavier load but having minimal dexterity. The operations carried out using the manipulators are conventional but at the same time require a highly transparent system which is mounted on the boom which, though resilient, must not exhibit backlash. The description of the apparatus is covered more fully in references [2] and [3] The articulated boom is the mechanical part of the bridge and its characteristics are worthy of note. The figures show its main feature is a horizontal spine which flexes laterally when under power. The end of the arm is equipped with pan, tilt and roll functions. The resulting structure is free from backlash and torsionally quite stiff but without any great lateral strength due to the limiting torque available from the joint drives. This 'lack' in no way restricts the functionality of the boom since it is not required to provide great lateral resistance and the 'weakness' can be considered an advantage in the event of an undesirable contact with the vessel. Each joint is computer controlled and the resulting 'snake' is able to work its way round the torus following a 'teach and learn' routine.

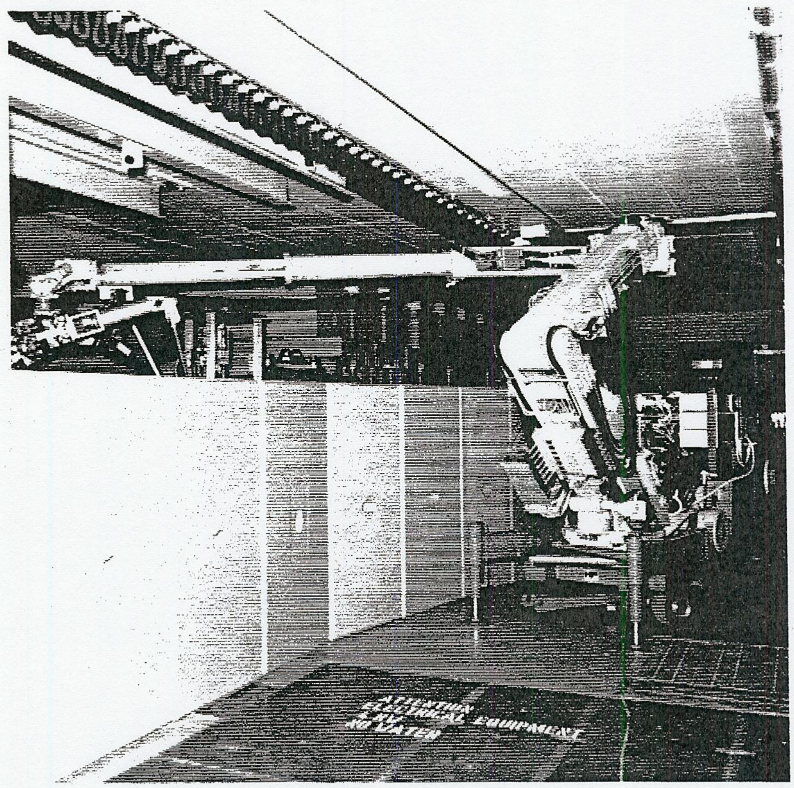
The relatively resilient structure is quite suitable for manipulative operations but would be suspect if subjected to forced oscillations from a device such as a power tool which was not externally restrained. Similarly, the limitations of harmonic drives mean that a boom of this configuration could not be used in an application where high lateral loading could take place. Both of these factors have to be considered by the designer of deployment systems for random remote operations.

4.3 Deployment Systems for Random, Remote Manipulator Operations

In the field of nuclear decommissioning or where remote work is to be carried out on equipment which has not been designed for remote maintenance, it is not possible to separate the unbolting of a component from the process of supporting the component. It is, therefore, unlikely that a system can be engineered where the manipulators can be removed and the deployment system can work as a crane. Also, the deployment system may be required to work through a number of planes giving rise to variable lateral loadings and at the same time provide adequate stiffness to resist forced vibrations if a cut-off saw or grinder is being used.

Figure 3 shows the manipulator deployment system known as Mantis II which is in operation at CERN.

Figure 3
MANTIS II
DEPLOYMENT
SYSTEM -
PHOTO - BY
COURTESY OF
CERN, GENEVA



This device is required to deploy the manipulators in an infinite variety of places and from any angle to perform an unpredictable series of tasks. Thus, for example, it must reach over a wall or under a table from the same position without changing its aspect or the manipulator mountings. Whilst the manipulator system is broadly similar to that used in JET, the facility is able to use hydraulic power and also avail itself of the services of a Support Vehicle which is equipped with a crane capable of lifting 1.1/2 tonnes at 4 metres and transporting up to 7 tonnes. It has been found that, although some form of tool support system is advantageous when integrated with the deployment system, the Support vehicle is best reserved to do the fetching and carrying.

This same philosophy is applicable to the remote dismantling of overhead structures where sections can be supported by one or more grabs whilst cutting is effected by servo-controlled tools mounted on a suitably dexterous arm.

As decommissioning of nuclear plant becomes more demanding, the need increases for greater levels of articulation in the manipulator deployment system. Since Chernobyl, there is a greater awareness of the need to provide some form of standby system. Experience on that site showed that it was insufficient to design something after the event. It is probably of equal importance to review the requirements of the deployment system for standby equipment as it is to define the parameters of the manipulators which will be mounted on it.

4.4 Common Design Problems

In the deployment system, it has been highlighted that a need exists for joints to have a high load capacity and no backlash. In this, conventional gearing is unacceptable and harmonic drive gearboxes have limited capacity whilst crane type hydraulic actuators tend to drift. The solution lies in the development of joints whose actuation incorporates full load braking of the applied torque without slip which can be released either by applied power or, in an emergency, by remote/manual control.

The deployment system has to carry, not only power and control for the end effector or manipulator system, but also similar services for itself. From the writer's experience and that of others, the routing of these services is a major headache especially with hydraulic supplies when space is limited (as it normally is). The positioning of piping and cabling, especially when negotiating orthogonal joints is very difficult apart from the inherent dangers of snagging flexure loops on hidden obstacles. In the CERN Mantis II system, the original design of trailing hoses and relatively straightforward rotary joints was substituted by a complex series of intersecting oilways which enabled fluid to pass through three consecutive joints without emerging as hoses. Whilst this has been successful, the design time required to achieve this does not allow for short construction periods and vindicates the need to plan ahead for equipment to be available for emergencies.

The experience gained in the design of this type of equipment has led to the conclusion that a complex deployment system would benefit from the concept of Locally Intelligent Nodes where a deployment arm is served by a hydraulic or electrical power bus running parallel to a data bus which would transmit command signals to a node having two or three degrees of freedom, Figure 4 shown on following page.

Each node would have its own control system and be able to supply sufficient data back to the master to enable an obstacle avoidance programme to be run.

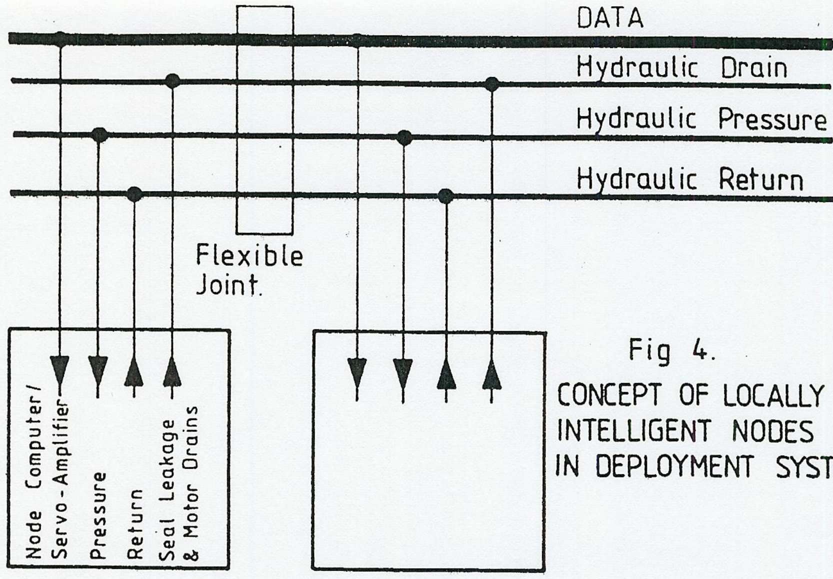


Fig 4.
CONCEPT OF LOCALLY INTELLIGENT NODES IN DEPLOYMENT SYSTEM

5. Conclusions

The paper has reviewed the various sub-systems which go to make up a complete remote manipulator operation or system. It concludes that insufficient advantage is taken by system designers of the benefits of sound feedback or audio-telepresence. Similarly, although great thought is put into adequate narrow field vision, more operator visual telepresence could be gained from background vision of the surroundings to enable him not to lose track of where he is while he concentrates on his work.

The manipulator deployment system is that in which much development work can take place particularly in respect of the design and control of joints. Backlash free systems having high load capacity in all axes are difficult to achieve and the development of braking elements which supplement the actuators represent a useful advance as do the simplifications in the design resulting from localised control and servicing of nodes having several degrees of freedom.

It would be unwise to neglect these items whilst concentrating on the more intellectually stimulating subject of tactile response.

6. Acknowledgements

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7. References

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