MASTER-SLAVE MANIPULATORS: TECHNOLOGY AND RECENT DEVELOPMENTS

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Introduction

Remote handling is the operation, in which manual tasks are performed without human intervention at the worksite. The use of remote handling equipment enables people to maintain a safe distance in hazardous work environments. The remote handling strategy adopted depends on the risks and the complexities associated with the task.

The simplest forms of remote handling devices are long reach tools, which extend the length of standard tools, providing a safe distance between the hazard and the operator. A remote handling tong consists of a gripper, a handle and a connecting rod. It can be installed in a shielding wall, hung on a carrying system (for use in a water pool), or carried by the operator.

If the task needs additional shielding and it can be brought to a worksite, handling can be done using an in-cell crane, a power manipulator or master-slave manipulators. The in-cell crane and power manipulator are used for handling heavy objects, where orientation of objects and precision in handling are not very important. They are usually controlled by push button switches.

Radioactive materials are handled in a heavily shielded room, called a hotcell, using remote manipulators. The cells are shielded with normal or high-density concrete walls of thickness ranging up to 2m. Hotcells are generally viewed through shielded glass windows.
Master-slave manipulators (MSMs) are the most widely used general purpose remote handling tools used in nuclear industry. In master-slave manipulation, human being is within the process, and his abilities are extended to the remote place.

An MSM has two arms: the slave arm, which is usually located in the hotcell and the master arm in the control station. When the operator grasps and manipulates the master arm, the motion of his hand is reproduced at the slave arm, performing the necessary task. In most of the cases, the master arm and the slave arm are made geometrically similar to each other. MSMs are usually employed in pairs and the operator manipulates the master arms using both his hands.

**Mechanical Master-Slave Manipulators**

Most of the mechanical manipulators are of through-the-wall type, where the slave arm remains in the hotcell, the master arm in the control station and the through-tube connecting these arms, passes through the shielded wall. The manipulator provides a mechanical linkage between the operator at the control station and the hazardous task inside the hotcell. The gripper of the slave arms are powered and controlled by the operator's hand through the master arm. From the task area, the operator gets visual feedback through a shielding window and force feedback through the manipulator. Mechanical MSMs are suitable, where the work area is constant and not too large, the force requirement is within the capacity of the operator and the task is not repetitive. DRHR has developed various types of mechanical manipulators with payloads ranging from 4.5 kg to 45 kg and volume coverage from 1 m$^3$ to 20 m$^3$. Several such manipulators are installed in various DAE units.

**Degrees of Freedom**

For the slave gripper to attain arbitrary position and orientation, the manipulators should have at least six independent motions. The gripper should also have a squeeze (open and close) motion to grip and release objects. In addition to this, the slave arms are usually provided with two or three supplementary electrical motions to increase their work volume.

**Types of Mechanical MSMs**

There are mainly two types of mechanical manipulator designs: articulated and telescopic.

All joints of the articulated arm are of revolute (articulated) type. Articulated manipulators allow transmission of forces up to a medium level. They have a small working volume and are suitable for hotcells with small wall thinness, typically made of lead.
Power Transmission

Power Transmission between the master arm and the slave arm is the most challenging task in manipulator design. When a master hand grip is moved, the corresponding slave gripper should also move by the same amount in the same direction. Moreover, any application of force/torque on the master arm should reflect on the slave arm and vice versa. Seven motions (or force) of the master gripper have to be converted into corresponding master joint motions (forces), transmitted across the cell wall to the slave in the hot cell and converted into motion (force) of the slave gripper. All transmission mechanisms should operate in parallel, so that, the slave gripper reproduces the trajectory of the master handle. Electrically actuated motions of the slave arm also have to be transmitted from the master to the slave.

Manipulators with telescopic arms have at least one linear (telescopic) joint. They can transmit larger forces and are suitable in larger hot cells with thick concrete wall shielding.

Rotation of every joint will result in movement of a large number of parts, relative to one another. For faster and accurate gripper positioning, the motion transmission should be rigid, positive and backlash-free. During handling, the operator will feel the forces due to manipulator dynamics, in addition to the external load, acting on the slave. Therefore, friction, gravity load and inertia of the manipulator are to be minimised, to reduce operator fatigue. The design should be highly optimised to meet contradictory requirements: low friction with low backlash and high rigidity with low inertia members.

Mechanical power transmission across the cell wall, is done using wire ropes, metal tapes, 4-bar mechanisms or shafts. Wire ropes and metal tapes
are lightweight, compact and flexible, compared to other transmission mechanisms. Within the master and the slave arms, spur gears, bevel gears, rack and pinion etc. are also used, for power transmission and motion conversion.

*Bilateral Control*

The coupling between the master arm and the slave arm must be bilateral such that, the forces acting on the slave arm must be reflected at the master arm and displacements produced at the slave arm must be able to produce a displacement at the master arm. The force reflection helps the operator to feel and control the applied force and helps him, to perform the task faster and more accurately. In addition to this, the back-drivability due to the bilateral coupling, makes the slave arm compliant with respect to the task and enables the slave arm to align itself, in response to the constraints imposed by the task.

*Balancing*

The manipulator joints are mechanically balanced, so that, the operator does not feel the weight of the manipulator during handling. It is generally achieved with adjustable counter weights installed on the master arm and in some cases, on the slave arm.

*Motion Locks*

Motion locks are used, to lock the manipulator joints rigidly in any position. They also facilitate installation and removal of the manipulator. In general, motion locks are made in three distinct units that can be operated independently: X-motion, Y-motion and combined Z-motion/ azimuth/ elevation/ twist rotations. The manipulator handle assembly also has its own tong/grip lock.

*Remotely Replaceable Jaws/Tong*

The only parts of the manipulator that come in contact with the objects in the hotcell are the jaw friction-pads of the slave tong. Friction pads need periodic replacement. By remote replacement, the jaws can quickly adapt to gripping surfaces of different sizes and shapes.
Materials
Material selection is of utmost importance in any manipulator design. To reduce the size and weight of parts, the material should have high strength-to-weight ratio. The material used in the slave arm should also have high radiation tolerance. The bearings should be of stainless steel, filled with radiation-resistant grease.

Electrical Indexing Motions
Indexing motions provide offset, between corresponding joint angles of the slave arm and the master arm. They are used to enlarge working volume and to reduce operator fatigue. Y-motion indexing allows the slave arm to be oriented in horizontal direction for installation and removal of the manipulator through the wall-sleeve. In addition to this, indexing allows the operator to remain in front of the window for viewing, thus reducing the required size of an expensive shielding window. Indexing motors are usually mounted on the master arm.

Extended Reach
Extended reach motion is the motorised telescopic extension of the slave arm, usually provided in manipulators used for larger hot cells. It is provided with a double telescope: the inner telescope for manual Z-motion and the outer one for motorised Z-motion.

Shielding
Shielding within the through-tube is provided as an optional feature in MSMs. It reduces the amount of radiation penetrating from the hotcell, at the through-tube level. Shielding is better achieved in manipulators of three-piece construction.

Sealing
Sealing isolates the hotcell atmosphere, from the outside. The through-tube of the manipulator may be unsealed for beta-gamma cells or sealed for alpha-gamma cells. Seals are also useful in inert gas cells containing toxic gases or airborne contamination. In the absence of sealed type construction, manipulators depend on booting, to prevent gas flow out of the cell.

Extended Reach
Master-Slave Manipulator (ERM)

The first two indigenous pairs of ERMs are installed at Augmentation of Cobalt Handling Facility, RAPCOF, Kota. The 9 kg capacity manipulator has a reach of 3.4 m from its shoulder joints. ERM has low friction compared to other manipulators.
Rugged Duty

High strength in rugged duty construction is achieved, by careful proportioning of parts and proper selection of materials. Mechanical transmission line incorporates step-up/step-down gearing, to improve its rigidity and to reduce loads in tapes and ropes. Such force/torque multipliers are used in azimuth, wrist and gripper tape/rope circuits. Handles of rugged duty manipulators incorporate a force-multiplying system, called pumping mechanism, for holding heavy weights, which are beyond the holding capacity of a human operator. Higher load-carrying capacity in rugged duty design is achieved, with a modest sacrifice in inertia and friction characteristics.

Manipulator Booting

The slave arms can be equipped with a flexible sleeve, called booting or gaiter, to protect them from contamination and to provide leak tightness to the hotcell. Indigenous booting is made up of polyurethane, which has excellent resistance to radiation, resistance to punctures, tears and abrasion and resistance to minerals oils, gasoline, animal oils, alkalis and ozone.

Indigenous Rugged Duty Master Slave Manipulator

The indigenous rugged duty manipulator (RDM) is designed to withstand the force that a human operator can exert, in normal operating position. It has a load-carrying capacity of 45 kg. Recently, 20 pairs of RDMs were manufactured by M/s HMT Machine Tools Ltd., based on the design and drawings supplied by DRHR. They are installed in the newly constructed PIED hotcells.
Three-Piece Design
A three-piece master-slave manipulator (TPM) consists of three distinct and easily separable assemblies: the master arm, the through-tube and the slave arm. The unique feature of 3-piece construction is that, its slave arm can be remotely replaced in the hotcell, using in-cell crane or power manipulator. This modularity reduces installation and maintenance time. Unlike other MSMs, TPM uses parallel rotating shafts for power transmission, along the through-tube. This feature is effectively used in indigenous TPM to provide sealing and shielding across the cell wall.

Sealed Type 3-Piece Manipulator
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Mobile Manipulators
In a mobile manipulator system, the slave arm of the manipulator is usually mounted on a transporter to increase its effective range. Unlike the mechanical manipulator, the slave arm of a mobile manipulator

Remote Missile Fuelling for the Indian Navy
Liquid fuels used in missiles are highly toxic. Missile fuelling had been done by operators wearing plastic suits covering their entire body. Fuelling involves aligning the ports of fuelling gun with that of missile, locking the gun to the missile body, opening the gun valve etc. A master-slave manipulator pair and other accessories were supplied to INS Tunir, Uran for remote missile fuelling.
should have its own mechanical power source, such as electrical motors or hydraulic actuators. The communication between the master and the slave should be either wireless or through electrical cables.

**Electrical Manipulators**

A simple electrical manipulator system consists of two kinematically similar arms: the master and the slave. The mechanical power sources of the slave arm are electric motors, which are mounted on the slave joints and gripper. The controller continuously monitors the joint angles of the master and the slave, using the joint angle sensors like synchro and potentiometer. It drives the slave motors to correct any deviation in angles between corresponding joints of the master and the slave.

The presence of external power source in an electrical manipulator, reduces the operator's handling effort and fatigue. In addition, the force available at the slave arm is not limited by the strength of the human operator. The presence of the transporter allows the slave arm to approach the hotcell equipment from different positions and directions, providing flexibility in equipment layout in the cell. The effective range of the slave arm is limited only by the range of the transporter and a single pair of slave arms can serve a large cell.

In hotcells using electrical manipulator, the task area is viewed using CCTV cameras mounted on the manipulator and at different locations in the hotcell. Use of CCTV cameras in place of expensive viewing windows, reduces the cost of viewing system.

**Hydraulic Manipulator**

Hydraulic actuators have high power-to-weight ratio compared to their electrical counterparts. Hydraulically powered manipulators can be used for handling heavy loads.
Servo Manipulator Installation

Two pairs of servo manipulators are installed at the Waste Immobilisation Plant, Trombay. Their master arms and slave arms are kinematically similar to each other and each of them has six joints and a gripper. The joints are powered by 2-phase AC servo motors. One of the challenges in design is to exclude electronic components from the slave arm. The only electrical components used on the slave arm are motors, potentiometers and cables, which have good radiation tolerance. All other components needed for control are kept near the control station, which is about 100m away (cable length) from the slave arm. The slave arms are mounted on a telescopic mast, providing a large effective range to the manipulator.

Indigenous Hydraulic Manipulator

The 6-DOF articulated manipulator is powered by hydraulic motors and hydraulic cylinders. The slave arm is controlled by a kinematically similar, but smaller master arm. It can handle a weight of 50 kg at a distance of 3m from its base. The manipulator was developed by Refuelling Technology Division based on the mechanical design and drawing by DRHR.

Wireless Controlled Manipulators

If the hazardous area is large and cannot be confined to a work cell (like outdoor environment), it may not be possible to use wire or fibre for power and signal transmission (tethered), between the control station and the manipulator. Similar situation may arise in areas, which were accessible once, but later become inaccessible or unsafe later due to the presence of explosives, radiation, toxic chemicals etc. In such cases, the manipulator needs to be transportable to the work area and be wireless controllable.
Advanced Manipulator Systems

Compared to mechanical master-slave manipulators, servo manipulators have a high potential in remote handling, due to their advantages described earlier. The major research in this area would be to make them more operator-friendly and more autonomous.

Telepresence Systems

Human-Machine Interface is a crucial element in the success of any remote operation. In ideal

Explosive Ordnance Disposal System for Ordnance Factory Khamaria (OFK), Jabalpur

The system was developed for handling ammunition boxes containing rejected fuzes of antitank mines. The boxes are to be picked up from a row of stacks in the ammunition storage rooms, brought to the disposal site, opened and tilted for transferring the fuzes into a pit for disposal. The system consists of a manipulator, a Remotely Operated Vehicle (ROV) and a device for remote removal of fuzes from ammunition boxes. The ROV houses a battery, communication devices, computer, CCTV cameras, laser range finder, sonars, bumper switch etc. Its four-axis manipulator can carry a weight of 30 kg at a distance of 2.5 m.

Stereo Vision System for Enhanced Teleoperation

A stereo vision system is being developed in collaboration with IIT Kanpur for enhanced visual feedback. Binocular images synthesised from multiple cameras will be presented to the operator, in a head mounted display. A head-tracking system will monitor the motion of the operator's head to control the orientation of remote pan-tilt cameras.

Wireless controlled manipulator and vehicle

Head Mounted Display (HMD) for the stereo vision system (under development)
telemanipulation, the operator should be able to move the manipulator as if it was his own arm and he should feel as if he is physically present at the remote site (telepresence). To achieve this, the operator should be presented the stimuli of the remote site (video, audio, force, touch etc.) and he should have the ability to control the remote site (master arm with instrumented gloves, head tracking devices etc.). Typical equipment needed at the remote site would include slave arm with anthropomorphic grippers, pan-tilt cameras, microphones and sensors for touch and force.

**Telerobots**

A robot is a reprogrammable manipulator, capable of performing repeated sequences of operations, without human intervention. It can relieve qualified operators from dull jobs and make remote operation faster, accurate and consistent. However, as robots need a good knowledge base about the environment, the task and themselves, they are more suitable for repetitive jobs in well-structured environments.

Telerobots are master-slave manipulators with some level of autonomy. Supervisory control combines autonomous control performed under human supervision with manual control. In systems with large time delays and lower communication bandwidths, supervisory control with computer at remote site, is essential, to perform any handling task.

As the majority of remote handling tasks need the sensory, manipulative and decision-making capabilities of a human being, MSMs will continue to dominate remote handling, until artificial intelligence and robot technology, make the robot self-sufficient to take decisions and act on them, based on intuitive information.

**Advanced Servo Manipulator**

A 25 kg capacity servo manipulator with supervisory control capabilities is being developed. Its master arm will have force reflection, so that the operator can feel the external force/torque acting on the slave. The manipulator will be computer controlled and it will have features like, motion scaling, force scaling, dynamics compensation for force reflection, indexing in world coordinates and teach & playback. The structure of the manipulator can be mechanically reconfigured to suit application.