ADVANCED SERVO MANIPULATOR: A MILESTONE IN REMOTE HANDLING TECHNOLOGY

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Introduction

Future nuclear installations would need a higher level of remotisation and automation, to improve their safety and productivity. Plants using Thorium-based fuels introduce additional problems in remote handling, due to the build-up of radioactivity in the U-232 decay chain. In such plants, operators can handle the material only behind thick shields, using reliable and advanced remote handling tools. In this context, we have recently developed an Advanced Servo Manipulator (ASM), based on in-house mechanical design and indigenous drives and controllers.

A servo manipulator consists of two arms: the slave arm and the master arm. There is no direct mechanical links connecting the master arm and the slave arm. The slave arm is usually kept in the remote hotcell and the master arm in the control room. During operation, as the operator holds and moves the handgrip of the master arm, the slave arm reproduces his hand movements and performs the necessary task in the remote area.

A servo manipulator can handle heavy objects with less operator effort. As mounting the slave arm on a transporter augments its operating range, a single pair of servo manipulators is sufficient to serve a large hotcell. It also offers flexibility in equipment layout, within the hotcell.

Although, there are many mechanical master-slave manipulator installations in various hotcells, only a few servo manipulator installations exist in the department.

ASM represents a new generation of servo manipulators with force reflection capabilities available to the human operator. The operator’s hand in the control station acquires the proportional force acting on the slave arm in the hotcell. Force reflection makes remote operation faster, safer and more accurate. Other major enhancements of ASM over earlier designs include, reconfigurable arm structure, higher payload and digital control. In ASM, we have provided advanced features in control and user interface, using advancements in digital microelectronics. Moreover, we have made it more flexible for future requirements.

Fig. 1: Slave Arm of ASM
Development of ASM involves meeting many challenging tasks in mechanical, electrical, electronics, control, software and radiological areas. The slave arm located in the hotcell, needs to be highly reliable and made from radiation-tolerant and washable components. Placing electronic components away from the slave arm is a design challenge. ASM controls involve real-time control of a non-linear, time-varying, multi-axis and coupled system for position trajectory as well as force trajectory. This article discusses important features and major sub-systems of the ASM.

**Mechanical Design**

We have designed the master arm and the slave arm kinematically similar to each other. The slave arm uses only radiation resistant materials and components. Ball bearings used in the slave arm are of stainless steel material, filled with radiation-resistant grease. Electric components used in the slave arm are radiation-resistant and of IP65 class. Materials used ASM are of high strength and lightweight.

**Degrees of Freedom**

For the end-effector to attain arbitrary position and orientation, six independent motions are necessary for any manipulator. In addition to the necessary six Degrees Of Freedom (DOF), we have provided an additional (optional) joint in the slave arm to increase its range. The additional range may be necessary in certain hotcells, where the manipulator has to approach areas beyond cell crane hook. In addition to the six or seven joints, arms have end-effectors. Fig. 2 shows the various axes and major sub-assemblies of the manipulator.

**Manipulator Structure**

The manipulator has articulated structure, with all revolute joints. It can be configured as elbow-down or elbow-up type, to suit the equipment layout in the hotcell. Elbow-down configuration is similar to the human hand. Fig. 3 shows the slave arm in elbow-down configuration.

It can also take a tabletop structure (like a robot), which can be mounted on a mobile platform. Mounting the slave arm on an overhead telescopic bridge crane, increases the effective range of the slave arm.

**Modular Design**

It is easy to assemble or disassemble the manipulator sub-assemblies for maintenance. The major modules of the manipulator are base, upper arm, forearm, wrist and gripper as shown in Fig. 2. The actuator assemblies of
joints, consisting of motor, resolver, brake, gearbox and potentiometer are also replaceable. Operator in the control station can replace the slave arm fingers, which are in the hotcell.

**Power Transmission**

Mechanical transmission elements transmit power from motors to joints. The major consideration in deciding motor locations and type of transmission linkages are joint size, joint weight, inertia, joint angle range, friction, rigidity and position error. Mounting the motor near a joint, will increase joint size and make the approach to task area difficult for the arm. It will also increase gravity and inertia loads of preceding motors. However, mounting it away from a joint will increase flexibility, position error and friction. It will also reduce the joint range, due to the mechanical coupling among transmission elements. Therefore, we have decided actuator locations judiciously to optimize the above factors.

Flexible elements like tapes and ropes were used as mechanical manipulators and previous model of servo manipulators was used for transmitting power between motor and joint. Although, they have lower size, inertia and friction, their maintenance and replacement need considerable plant downtime. Therefore, we have designed ASM with rigid mechanical transmission elements like spur gears, bevel gears, shafts and 4-bar mechanisms. To improve force reflection characteristics, we have kept low the gear ratios in joints.

During operation, the master arm converts every movement of its handgrip into joint rotations. Moreover, it converts the torque generated by its motors into force and torque at handgrip, for providing force reflection to the operator. In the slave arm too, the conversion of force and motion between the gripper and joints are bi-directional. Therefore, we have designed all mechanical transmissions in master arm and the slave arm to be back drivable. Back-drivability also helps the slave arm to align itself to the job, in response to the constraints imposed by the task.

All major joints of the manipulator are mechanically counterbalanced. Motors mounted near the base serve as counterweights too.

**Wrist**

ASM has a small wrist as compared to the size and weight of the object it can handle. With a compact wrist, the manipulator can handle objects near a table, wall or other obstacles. Making a compact wrist is one of the difficult tasks in manipulator design. The wrist has spur gear pairs, bevel gear pairs and a differential mechanism, to convert rotations of two parallel shafts into roll and pitch motions of the end-effector. Wrist also transmits mechanical power to actuate the end-effector.

As we intend using the slave arm as a robot also, we designed its wrist as **spherical type**, whose orientation axes all intersect at a point. This is a deviation from all mechanical master slave manipulators and servo manipulators. Existence of a closed inverse kinematic solution is essential for robot control and a spherical wrist can meet this requirement.

**End-Effectors**

ASM has two types of end-effectors: slave arm gripper to hold objects in the remote area and the master arm handgrip to generate gripping command.

The major challenge in gripper design is reduction of gripper size and weight. The ability of the manipulator to orient its gripper (dexterity) increases with decrease in gripper length. Moreover, the increase in gripper length is not desirable from load carrying capacity, position error and force reflection points of view. ASM gripper, which can open upto 100 mm and handle a weight of 25 kg, has a length of only 170 mm.
The gripper is parallel jaw type, whose contact surfaces remain parallel, irrespective of their opening. For better gripping, the contact surfaces are made from rubber. They wear out easily by rubbing with other objects. Their frequent contact with radioactive materials contaminates them easily. As they need frequent maintenance, the jaws are made to be remotely replaceable in the hotcell. Jaw replacement also helps in handling odd shaped objects with non-planar gripping surfaces.

To ensure firm gripping, we have provided a flexible member in the transmission mechanism between the motor and the gripper. It reduces the variations in gripping force arising from factors like motor torque fluctuation.

**Master Arm**

Speed (task completion time), accuracy, ease of learning, operator fatigue and joint coordination are the major factors deciding the usability of an input device. Input devices of a computer, such as mouse or joystick, can control and coordinate two or three variables simultaneously. However, a typical remote handling task, needs control of six configuration variables of the end-effector. Therefore, we have designed a master arm as an input device for simultaneous control of six configuration variables. Operator can sense as well as control three components of force and three components of torque through the master arm. All these variables are controlled and sensed through the master handgrip. In addition to this, the operator can feel and control the gripping force and gripper opening of the slave arm through the master handgrip.

The master arm and the slave arm have the same structure and link lengths. The corresponding motors of the master arm and slave arm are identical. The major difference between the master and slave arms is in their end-effectors and load-carrying capacities.

Gear ratios in the gearboxes of the master arm are so decided, that the maximum joint torque is only one-third of the corresponding slave joint torque. Reduction in friction and inertia, due to the lower gear ratios in master arm, reduce operator effort and give better force reflection. Moreover, the resulting lower torque limit protects the human operator from any controller malfunction.

**Actuators and Sensors**

ASM uses brushless AC servomotors as mechanical power sources. These are permanent magnet synchronous motors with wound stator and permanent magnet rotor.
The combination of an inner permanent magnet rotor and outer windings offer low rotor inertia, efficient heat dissipation and reduction of motor size. Absence of brushes reduces noise, EMI generation and eliminates the need of brush maintenance. These motors have good linear torque-current relationship, which is essential for accurate force feedback to the operator. Motor selection is standardized such that, only motors with three ratings are used in the manipulator, out of the 16 motors in the manipulator.

Between trapezoidal and sinusoidal types of motors, we have selected sinusoidal type for our application. Space-vector modulation technique creates the sinusoidal voltage waveform applied to the motors. As sinusoidal currents drive sinusoidal motors, torque ripple is eliminated. For real-time control of torque and speed, Field Oriented Control algorithm is used. As this method is accurate in both steady-state and transient mode of operations, over sizing of power module was not necessary. The transient currents are continuously controlled in amplitude.

The motor has an inbuilt resolver to sense its rotor position. The drive card converts the analogue resolver signal into logic pulses. These are used for electronically switching the stator windings in proper sequence to maintain rotation of the magnet assembly. The servo control loop also uses the resolver signal for position feedback. As the resolvers take multiple turns within the joint range, they alone cannot provide absolute joint angles. Multi-turn potentiometers mounted on the joints provide absolute initial joint angle, which is used for initializing the absolute resolver output.

All motors are integrated with failsafe brakes. Operator can apply brake to all joints to hold the manipulator in position. During power failures, the brakes prevent uncontrolled joint movement and retain the held object in position. Other malfunctions also result in automated application of brakes.

We have used only radiation-tolerant motors, brakes, sensors and cables in the manipulator. These are IP65 rated, to enable decontamination of the entire slave arm by washing. We have used only shielded leads to reduce noise pickup from motor drives.

### Control System

The Advanced Servo-Manipulator Controller (ASMC) is based on distributed digital control. Compared to an analogue control system, a digital system has more flexibility, long-term stability and less cable handling problems.

ASMC consists of operator interface, co-ordination computer, joint controller and servo drives. Fig. 6 shows the architecture of the control system. The coordination computer communicates with joint controllers on a shared RS485 serial communication link, while the joint controller communicates with the corresponding master and slave servo drives over dedicated RS422 links.

ASMC provides the following functionality:
1. Master slave follower
2. Force reflection to the master arm
3. Indexing of joints
4. Brake operation
5. Torque limiting
6. Artificial force reflection
7. Status reporting
8. Fault protection.

Compared to a centralized processing system, a distributed system reduces individual unit processing requirements. It also supports high update rate and large number of input-output signals required by each servo loop. In addition to this, it is less vulnerable to system failure. It also needs less software maintenance.

All master servo drive hardware and software are identical. Likewise, all slave servo drive hardware and software are identical. DIP switch settings configure them for respective
Common software across drives/joint controller reduces the amount of software. The architecture allows the necessary quick data transfer between the master drive and the slave drive. Data sampling, control and information transfer are accomplished in real time.

A rack mounts all ASMC components. Radiation-tolerant cables connect ASMC to the motor and sensors. The length of cable connecting the control cabinet and the slave arm can be up to 100 m.

**Servo Drive**

Each joint of the manipulator arm is driven by a separate servomotor and drive. There are 16 drives for eight pairs of master-slave motors in the system. Each servo drive collects data and controls the corresponding joint. The power section of the drive is based on integrated power module. The current and velocity loops of the servo control are implemented using a commercially available servo control IC. The position loop and drive control software are implemented on cygnal 8051F120. The servo control IC allows the user to configure different types of motors, position feedback devices and communication protocols. The system also allows feed forward control, in addition to existing PI control. Fig. 8 shows the internal block diagram of the drive.

The manipulator joints do not have encoder, but their motors have inbuilt resolvers for position feedback. As the servo controller IC accepts only encoder input, IC AD2580 does the necessary resolver to incremental encoder signal conversion. The incremental encoder
signals update a 32-bit counter inside the servo controller IC and this count is later converted to joint angle.

AD2S80 provides only the position of the motor shaft and not the necessary joint position. To get the initial position of the joint, signals from the joint potentiometer are fed into the micro-controller. This initial position is loaded as the initial count into the 32-bit counter. Fig.9 shows the block diagram of the servo control.

The overall specification of the drive is presented below:

- Position loop update rate: 500 Hz
- Velocity loop update rate: 5/10 KHz
- Current loop computation time: 6 μs
- PWM Carrier frequency: 70 kHz
- Continuous output current: 5 A (750 W)
- Overload output current: 15 A
- Max. RS232C speed: 115.2 kbps

**Joint Controller**

ASMC has eight joint controllers, one for each master-slave joint pair of the manipulators. A joint controller exchanges information between the servo drives of the corresponding joints, in real time. In addition to this, it supports indexing, joint alignment, brake control and fault protection. Fig. 10 shows the hardware block diagram of the joint controller.
The processor on board is cygnal 8051F120 running at 55 MHz. This processor is different from the processor on the servo drive board. The processor was selected on the basis of the control requirements, high integration of peripheral components like timers, UART, ease of developing software using ‘C’ language and JTAG-based debugging capabilities. As the processor has pipelined architecture and is running at 55 MHz, i.e. 55 times faster than the regular 8051, the traditional MIPS constraint (1MIPS) could be overcome. All these MIPS are available, just for one joint controller, and we have eight joint-controllers. When we implement robot mode in ASM, the Spartan IIE FPGA on board will act as a co-processor to the 8051F120.

A joint controller communicates with the coordinating PC and corresponding master and slave drives. Parameters are updated to the drives once in every 16 mSec.

From the PC, it gets limits for position, speed and torque; gain factors for position and speed; operator applied brake status and indexing position. It provides positions, speed and torque of joints; motor brake status; motor temperature status (hot/ cold) and drive fault status to the PC for display and diagnostic purposes.

From the master drive, it gets position and speed of the joint. It updates the drive with reflecting torque and limits for position, speed and torque.

Similarly, it provides required position and velocity to the slave drive. It also updates the status and limits of position, velocity and torque of the joint from the slave drive.

**Coordinating Computer**

We have used an industrial PC based on Pentium processor as coordinating computer in the ASMC. The PC uses RS422 port to communicate with the operator keyboard and optic fibre cable to communicate with joint controllers. The computer controls all the master and slave joint controllers.

**Operator Interface**

As described earlier, the master arm is the major operator interface in ASM, which can input (position) and output (force) six variables in coordination. Operator uses its
handgrip for control of gripper opening and closing, sensing the gripping force and applying the required force.

A keypad is mounted on the master handgrip. It has keys for selecting force reflection ratio and torque limits. Operator can select a joint for indexing and start indexing motions in forward or reverse direction. Toggle keys are provided for applying/releasing brake on all joints and locking/unlocking the slave gripper. Operator can use the keypad with his thumb, while holding the handgrip.

Operator uses the PC during the startup of the system. The PC displays the joint variables of the master and slave, status of the settings and error conditions, if any. The administrator uses it for setting the control parameters. Sound alarm also indicates the status of the system.

Like other servo manipulator systems, here also CCTV cameras will be used for visual feedback of the remote environment.

**Master Slave Operation**

During master slave manipulation, operator holds and moves the master handgrip. The slave gripper, which is in the remote area, follows the movement of the master handgrip doing the necessary tasks.

The mechanical design of the manipulator is such that, when all joint angles of the slave arm match with those of the corresponding master arm, their end-effectors will also match with their configurations. Therefore, the primary role of the controller is to match the angles of all the slave joints to corresponding master angles, at every instant.

As the operator moves the handgrip, position sensors (resolvers) mounted on the joints sense the master configuration. The controller computes the instantaneous errors between corresponding joint angles of the master and slave, converts them into a set of currents and applies them to the slave motors. Velocity errors are also added to the position errors to stabilize the control system. Fig. 9 shows the closed loop control for the same.

Gains of each joint controller are separately tuned, to achieve accurate and stable trajectory, following the slave joint with respect to that of the corresponding master joint. Fig. 12 shows the typical trajectory of slave motor with reference to the master input.

Gripper operation involves closing and opening the gripper and applying the necessary gripping force. Though it involves position control as well as force control, we use the gripper controller identical to that of other joints. During gripping, as the operator closes the handgrip, the slave fingers move and touch the object. Further closing of the handgrip will increase position error, as the object surface restricts further movement of slave fingers. As the force generated is proportional to the position error, operator can control the gripping force by controlling the handgrip opening.

**Advanced Features**

The total digital control system used in ASM provides flexibility in control and user interface. A description of some of the advanced features implemented in ASM follows.
**Force Reflection**

ASM is a bilateral manipulator, which allows the force acting on the slave gripper to be reflected on the operator’s hand. Force reflection makes the operator aware of any resistance in movement, provides a feeling of the load being handled, and helps him to control the applied force. It prevents the operator from unknowingly applying damaging forces to the object being handled, to the nearby objects or to the manipulator itself. Ability to feel and control the applied force helps the operator to perform the task faster and more accurately. It is an inherent property of mechanical manipulators, that no significant loss of mechanical power or motion occurs, in their transmissions between the master and slave. However, implementation of force reflection is a difficult task for servo manipulators.

In ASM, we have provided motors in the master joints also to generate force. These motors operate in the torque control mode. As it is difficult to use force sensor in radiation environment, the slave motor current (which is proportional to the slave motor torque) is taken as an indication of slave load. The slave motor current is applied on the corresponding master motor, after necessary scaling, filtering and compensation. The direction of the torque generated at the master motor is opposite to that applied on the corresponding slave motor. The Master arm converts the motor torques into force and torque of handgrip, providing force feedback to the operator, who is holding the handgrip. Operator can change the Force Reflection Ratio (FRR), which is the ratio of the force reflected on the operator’s hand to that acting on the slave end effector, from zero to one. Fig. 13 shows the implementation of bilateral control in ASM.

Friction in motors, brakes, gears and mechanical transmission elements increase operator effort in handling the manipulator. We have implemented a friction compensation scheme to reduce the effects of friction. Fig. 14 shows the applied master current and measured slave current of ASM. Initially FRR is 0 and no current is applied to the master. FRR is 0.5 in the second part.

**Indexing**

In ASM, the range of the slave arm is more than that of the human arm. We have provided indexing motions to
the positioning axes, to use their entire range effectively. In indexing mode, an operator can rotate selected slave joints, without rotating their corresponding master joints. Indexing also helps the operator to control the manipulator sitting in a comfortable posture.

The Operator can select the joint for indexing and command the joint to move in the desired direction through the handgrip keypad. After indexing, though there will be a mismatch between the master and slave joint angles, operator can continue master slave operation in the mismatched positions.

**Torque Limit**

ASM can handle 25 kg load (Fig. 15). However, to protect the manipulator and nearby objects during accidental collisions, it is desirable to operate it at a lower capacity. The operator has an option of limiting the manipulator capacity to a specified load using the handgrip keypad. Only when the manipulator fails to handle the object that he needs to increase the torque limit. This feature is also useful in handling fragile and delicate objects.

**Soft Joint Limits and Artificial Force Reflection**

The master arm and the slave arm can have independent joint limits and their complex workspaces are modelled in the computer. The joint limit settings will prevent slave joint to move beyond the set limits, even if the operator tries to move the corresponding master joint. A sound alarm indicates whether any joint of the master arm or slave arm has reached its limit.

In the force reflection mode, when a master or slave joint approaches its limit, the operator gets a repelling force on his hand, resisting him from moving closer to the limit. It helps in preventing internal collision of manipulator parts. Other undesirable conditions, like large position error, also result in a repelling force to the operator.

**Conclusion**

Development of the Advanced Servo Manipulator has been completed and the manipulator is available for demonstration. The digitally controlled manipulator has...
force reflection and other advanced capabilities. The development strategy was based on in-house mechanical design and indigenous control hardware and software.

To enhance its performance further, we will be providing features like motion scaling and compensation for manipulator dynamics to ASM. We are also planning to use ASM in telerobot mode, where the slave can perform autonomous operations without operator assistance.

We have taken up the development of Four-Piece Servo Manipulator (4PSM) from this core technology. Conventional servomanipulators need hotcells specifically designed for their installation. However, we can install 4PSM in conventional hotcells, which were designed for mechanical manipulators. It will be more operator-friendly than the conventional mechanical manipulators. We are also developing other servo manipulator systems, including a miniature servo manipulator and a surgical robot.

We have developed ASM with flexible and expandable features, for ease in enhancement and customization to meet user requirements. The indigenous technology has laid a foundation on which we can develop many advanced robotic systems in future.

**General Specifications**
- Degrees of freedom: 6 (+1 optional)
- Payload: 25 kg (at all positions)
- Maximum reach: 1.2 m
- Gripper opening: 100 mm
- Force reflection ratio: 0 to 1.0, subjected to a maximum force of 8 kg