An Evolution of Remote Handling Technology for the Indian Nuclear Research and Industry Scenario

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Abstract. Remote Handling is an essential tool for radioactive material handling and nuclear fuel reprocessing. Division of Remote Handling and Robotics, Bhabha Atomic Research Centre has been working on the development of remote handling tools for in house applications. The experience in each development has germinated the development of a more advanced system. This paper tries to graph this evolution of remote handling technology as an indispensable part of the Nuclear Fuel Fabrication and Fuel Reprocessing. The paper also encompasses a moderately detailed description of the methodologies associated with the development.

Keywords: Remote handling · Master slave manipulator · Servo manipulator

1 Introduction

Remotization plays a vital role in all nuclear installations. Plants using Thorium based fuels introduce additional requirements in the U-232 decay chain. In such plants, operators can handle the material only behind thick shields, using reliable remote handling tools. In radioactive material handling, uncertainty in task definition and precise descriptions makes fixed automation difficult to apply. Hence, the majority of remote handling operations are carried out through the Master Slave manipulators. In general, a Master Slave manipulator consists of two arms – the Slave arm located in a hazardous area and the Master arm in the control station. When the operator grasps and manipulates the Master arm, the motions of his hand are reproduced at the Slave arm performing the necessary task. Division of Remote Handling and Robotics, Bhabha Atomic Research Centre has been involved in the design and development of Master Slave manipulator systems, since long. The development process has evolved with time circumscribing change and advancement ranging from basic technology paradigm to more detailed and involved control engineering features and methodologies. A streamlined overview of this evolution will be presented in subsequent sections. The description of the evolution process, for ease of tracking, will be decoupled into evolution of basic approach to remotization and evolution of controls.

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2 Evolution from Mechanical Master Slave Manipulator to Electrical Servo Manipulator

The venture started with the construction of Mechanical Master Slave Manipulator [1, 2]. The mechanical manipulators are most generally through-the-wall-type, where a through-tube passing through a shield wall between the operator and hot cell connects the Master and Slave mechanisms. The basic layout is shown in Fig. 1.

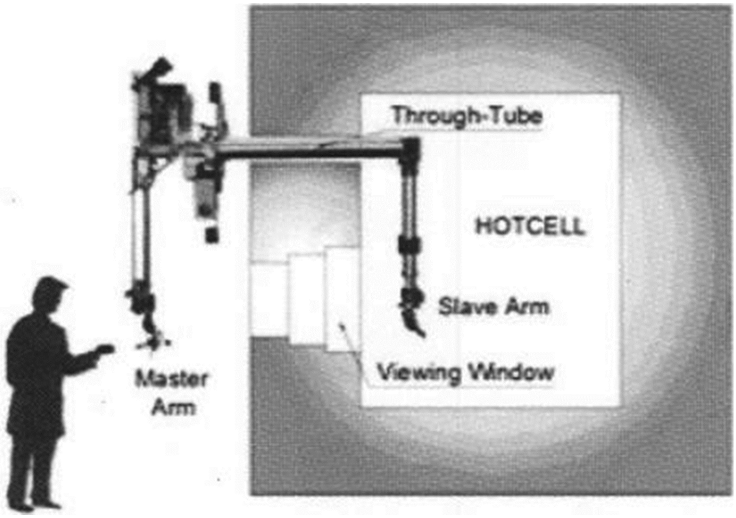

Fig. 1. Basic layout of mechanical master slave manipulators in hot-cell

There are mainly two types of mechanical manipulator designs: telescopic (Fig. 2) and articulated (Fig. 3). The fundamental difference between the two is that in an articulated manipulator all the joints are revolute while in a telescopic manipulator, one or more joints may be prismatic. Typically, each arm is a 6 degree of freedom serial mechanism. The mechanical coupling between the Master and the Slave arm is designed to be bilateral such that the forces acting at the Slave arm are reflected back to the Master arm in order to render the operator a real feel of the remote environment.

The mechanical coupling between the Master and Slave manipulator evidently limits the degree of remotization. The slave arm has to be fixed at one point only, in the hot-cell. Force reflection from Slave arm to Master arm, being unchangeable, often fatigues the operator after prolonged operations. All these practical problems led to the development of Electrical Servo Manipulators.

In Electrical Servo Manipulators, the Slave arm and the Master arm are coupled electrically/electronically and no mechanical coupling between them is present. The slave arm is actuated by motors. The controller, continuously monitors joint angles of Master and Slave arms using sensors like potentiometer and resolver, and drives the Slave motor appropriately to correct any deviation in angle between corresponding joints of Master and Slave. Force reflection, at Master, rendered by mirroring Slave motor

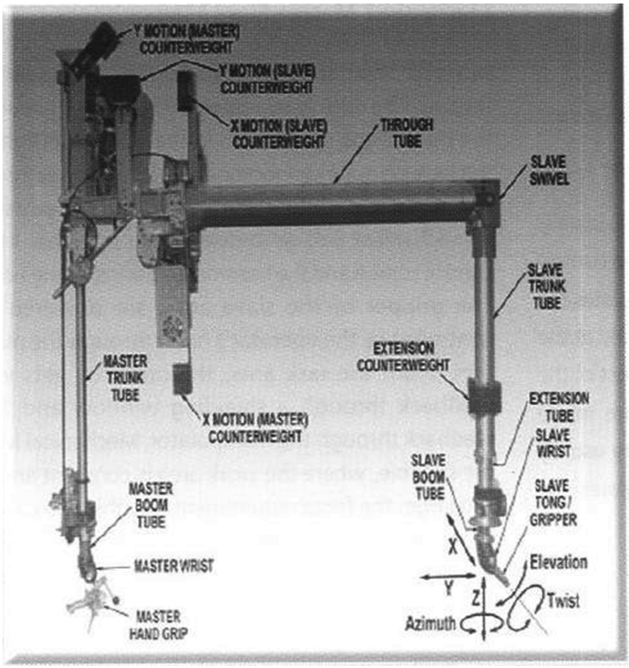

Fig. 2. Telescopic manipulator

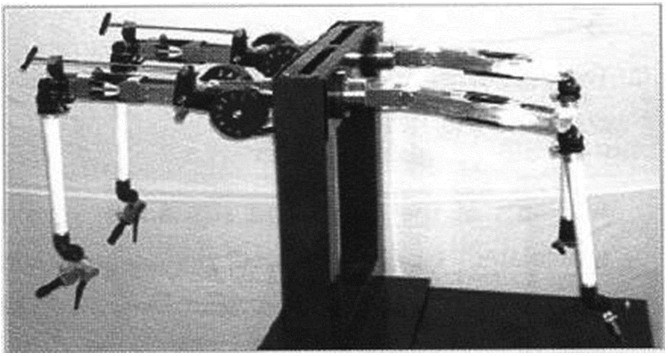

Fig. 3. Articulated manipulator

current on the corresponding Master motor, can be scaled through a program thereby offering the operator the opportunity to work at his/her comfort level without fatigue. The slave arm now does not have to be fixed to the master arm physically, and a transporter can be used to move the Slave arm required to approach hot-cell equipment from different positions and directions, providing flexibility in equipment layout in the hot-cell. The effective range of the Slave arm thereby increases manifolds, and even a single pair of Slave arms can serve a large cell. The task area is viewed using CCTV cameras mounted on the manipulator and at different locations in the hot-cell. This generation of manipulators are called the Advanced Servo Manipulators (ASM) [3] (Fig. 4).

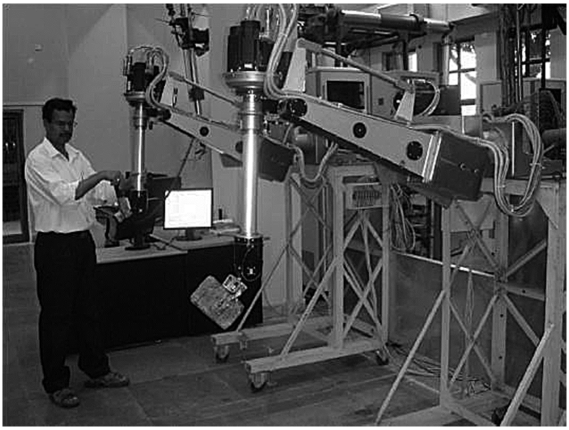

Fig. 4. Advanced servo manipulator

A particular variant called the Four Piece Servo Manipulator [4] (FPSM) has been developed for hot-cells where the support arrangement for ASM (e.g. transporters etc.) is not available. The FPSM (Fig. 5) can be installed through the wall sleeves of existing hot-cells.

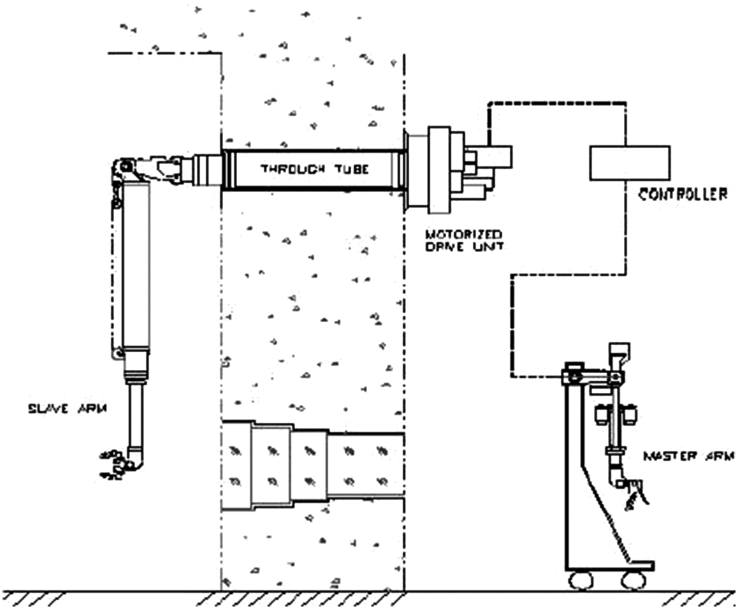

Fig. 5. Four Piece servo manipulator

Once the remote handling technology has undergone a paradigm shift from Mechanical Master Slave Manipulator to Electrical Servo Manipulators, further development has been generational, bringing in improvement in the control architecture and functional features in both hardware and software. This will be discussed in the next section.

3 Evolution of the Electrical Servo Manipulator Control Architecture and Features

The Advanced Servo Manipulator (ASM), till now, has 2 generations of development which are discussed in subsequent subsections.

3.1 ASM Gen I

The control architecture of the first generation of the Advanced Servo Manipulator (ASM GEN I) is shown in Fig. 6. It is a multi-axis bidirectional tightly coupled digital distributed control system. The main components of the Servo Control System are the actuator, the drive, the joint controller, the Master computer and the communication pathway that connects them all. All the ASM developments use Brushless AC Servo motors with inbuilt failsafe brakes and Resolver as the actuators. The control of these actuators and hence the entire manipulator control is centred on indigenously developed BLAC Servo motor drives. The functional block diagram of the motor drive is shown in Fig. 7. The position control is based on PI control (Fig. 8). It is cascade control architecture as evident. The Speed PI control and Torque PI control is built into the Servo Control IC, while the Position PI control is implemented in the Joint Controller, which in turn communicates with the Master Control PC.

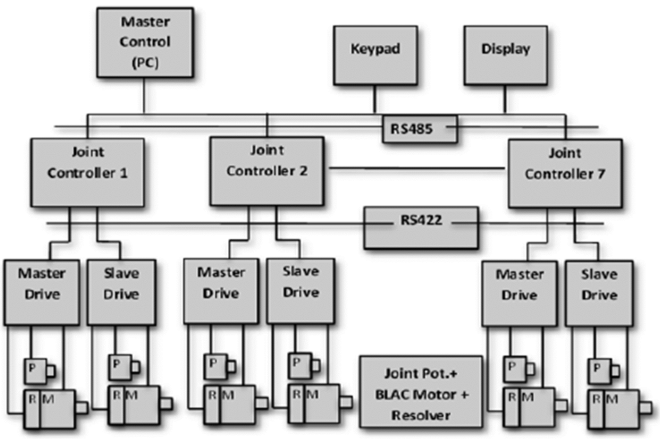

Fig. 6. Control architecture of Gen I Advanced servo manipulator

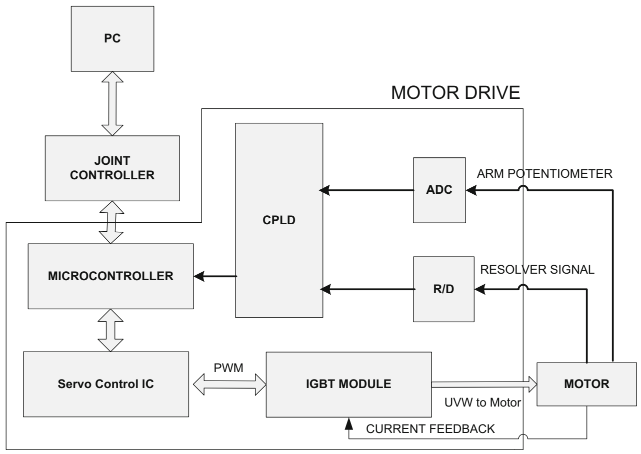

Fig. 7. Functional block diagram of motor drive

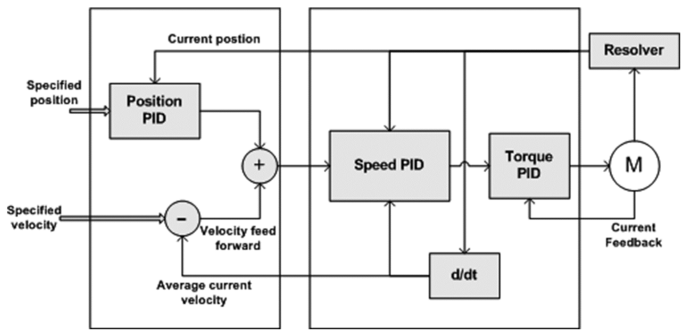

Fig. 8. Position Control system

The functionalities achieved in Gen I ASM control:

1. Master Slave Follower Mode - Continuous Master to Slave position tracking for all joints
2. Force Feedback mode - Continuous Slave to Master motor torque/current tracking with a programmable force reflection ratio
3. Indexed Motion mode - Pre-setting of Slave arm to a desired pose before starting Master Slave operation through a Human Machine Interface (in this case a keypad). After indexing is completed, the operator can continue Master Slave operation from the set positions of Master and Slave joints.

3.2 ASM Gen II

The 2nd Generation of ASM opened up a wide range of opportunities for the technology. This has been made possible by a change in the control architecture [5] (Fig. 9).

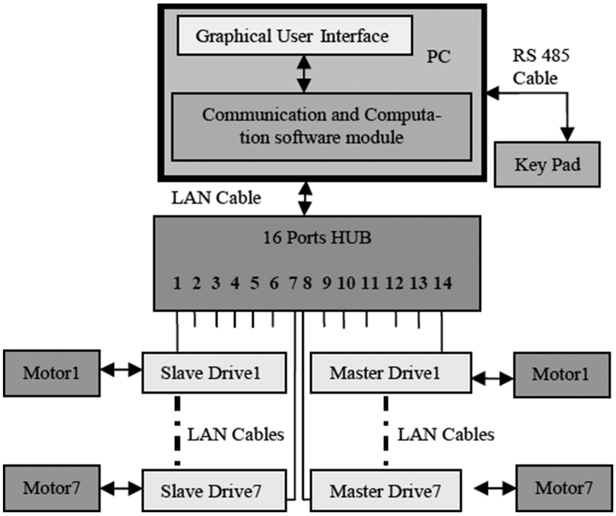

Fig. 9. Control architecture of Gen II Advanced servo manipulator

In Gen I control architecture the Joint Controller is microcontroller based embedded system with limited computation power. In Gen II, coordinating computer has become major control loop executive, thereby increasing the flexibility of implementing computation intensive features for intelligent and seamless human-robot-environment interface. In addition to the already existing features from Gen I, the functionalities achieved in Gen II ASM are:

(1) Robot Mode - The slave arm can be controlled directly from the coordinating PC without using the Master arm either in Joint space or in world coordinates. The control software also provides features for programming motion sequence scripts for the Slave arm. Apart from the Manipulator end effector position, the manipulating forces exerted by the end effector can also be simultaneously controlled [6].
(2) Teach-n-Playback Mode - In case of a repetitive job in an episodic environment (e.g. pick up some object from a predefined place and placing it at some other predefined place), the operator can teach the Slave arm the required sequence of motions, which will be recorded in the system and later played back by the Slave arm. The playback speed can be varied and the playback sequence can be totally reversed also.
(3) Constrained Motion and Obstacle Avoidance - This feature through artificial forces at the Master arm guide the operator to maintain motion along predefined workspace constraints (e.g. when manipulating objects in a cylindrical pipe, the preferential direction of motion is the cylinder axis; when performing welding on a surface, preferential motion should be confined to the plane of welding) while avoiding predefined workspace obstacles which the manipulator should not hit [7].

Besides these, methodologies like friction compensation [8] for faithful and accurate force reflection from Slave to the Master arm, have been developed which have enhanced system performance and added to the capabilities of the technology.

3.3 Further Development in ASM Control Engineering

Till Generation II, for Joint angle sensing, in addition to Resolvers, absolute position feedback devices like potentiometer was required for power-up initialization, because the Resolvers, although accurate and reliable otherwise, cannot provide the last joint position at system power-up. Every extra electro-mechanical component like potentiometer adds to the maintenance issues of the system. In recent development of a new version of Servo drive, an onboard NVRAM periodically stores the data from the Resolver so that the last known actuator state can be fetched during the next power cycle for initialization. This feature eliminates the need of any absolute position feedback device. Also, in the earlier system, configuration of the drive had to be done through a specific JTAG interface. In the newer version of the drive, all these configurations can be done through the uniform LAN communication backbone.

3.4 Performance Evaluation

Although performance evaluation of the system is not directly the focus of this paper, for the sake of completion, the most fundamental capabilities of ASM namely Master Slave Follower and Force Reflection have been evaluated and graphically illustrated. A detailed coverage of all the other features can be found in [5–8]. In Fig. 10, the overlapping of the motion profiles of the Master and Slave joint indicate proper Master following of the Slave. In Fig. 11, the reflected Master torque profile is same as that of

Fig. 10. Master to slave position tracking

the Slave torque profile, only scaled down and spurious noises smoothened down for operator ease.

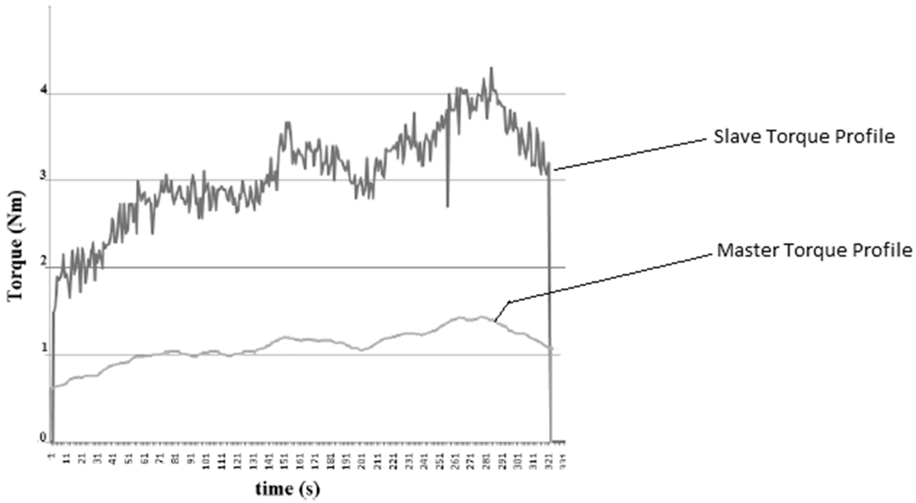

Fig. 11. Slave torque and reflected master torque

The accuracy and repeatability of the ASM Gen II in Robot Mode has been evaluated according to ISO 9283 [9]. They were found to be respectively 27.74 mm and 8.74 mm respectively.

4 Application of Master Slave Manipulator Technology

Mechanical Master Slave manipulator, since long time have found wide application in hot-cells across different facilities of the Department of Atomic Energy, Govt. of India. A master slave manipulator pair and other accessories were supplied to INS Tunir, Uran, for remote missile fuelling. Gen II ASM is now ready to be installed at Waste Immobilisation Plant, Bhabha Atomic Research Centre. One variant of FPSM is going to be installed at Tarapur Atomic Power Station for Reactor maintenance jobs.

5 Future Developments

The success obtained in the present developments has motivated us to delve into newer avenues. The foremost of them, which in future, may form the Generation III of Servo manipulator technology is the introduction of a wearable exoskeleton as the Master device and its subsequent interfacing with the Slave manipulator. Such systems will not only be more user friendly, but will also be able to provide richer haptic (force feedback) experiences. Robot assisted surgery is another futuristic technology for which we are developing reliable and accurate miniature master slave manipulator systems.

6 Conclusion

The advancement of remote handling technology undertaken by Division of Remote Handling and Robotics, BARC has been systematic and progressive, adding capabilities to each version learnt from the disadvantages and pitfalls of the previous. This has boosted confidence and self-reliance in nuclear fuel handling and reprocessing which is an unavoidable part for closing the Nuclear Fuel Cycle.

Also, it is expected that the technology, still progressing, has matured to an extent which can be accepted by diverse application sectors, other than nuclear, e.g. Chemical, Pharmaceutical etc. The evolution still goes on.

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