# Development of a 15 kg servo manipulator for remote handling applications

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**Abstract**

Remote Handling is one of the prominent areas of research and development for the nuclear facilities for the remote manipulation of irradiated nuclear fuels and structural materials inside Hot cells/ containment box.. The standard coding for the Remote handling devices for radioactive materials is covered as part 1: General requirements under ISO: 17874-1:2004 & part 3: Electrical master-slave manipulators (Servo Manipulator) under ISO:17874-3:2019. Though the master-slave mechanical manipulators have found wide applications in the nuclear domain especially in the hot cells, but recently the electric manipulators find its application in both nuclear fuel reprocessing and fabrication and in carrying out complex tasks inside the hot cells. This also finds its application in the decommissioning operations of nuclear facilities.. Under the mobile manipulators it is further classified into power manipulator and servo manipulator. The servo manipulators are closed-loop feedback system, which enable the sensing of slave side forces and reflect it on the master end. This makes the operator feel the slave environment remotely as tangible forces on the slave end-effecter are directly sensible. The dual arm design makes it further more easy to perform complex tasks with delicate handling of the slave objects. A 15 kg payload capacity servo manipulator was designed, developed and qualified at IGCAR. The real time force synthesis is done using the Jacobian matrix linearizing method for the inverse kinematic and force synthesis and the Jacobian matrix is constructed from the Jacobian generating vectors by the slave side manipulator pose/orientation. This is done by directly networking all the servo drive controllers and reading the slave motor encoder positions. Further, the motor torque is evaluated from the motor currents from all the slave joints and the torque vector is constructed. By calculating the work done by the manipulator the end effecter Cartesian forces and the direction vectors are computed and the same is applied on the master end thereby simulating the slave environment. This paper deals with the design of the servo manipulator for the remote handling application.

## INTRODUCTION

Remote handling is one of the challenging tasks in the hot cells for the handling of radioactive materials, tools and equipments. It is always a big requirement for the remote manipulation in the hot cells which requires the use of the master-slave manipulators. Various categories of manipulator according to Ref: ISO: 17874-1:2004, ISO 17874-1:2010 are shown in fig.1.

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| FIG.1 Classification of manipulator used in hot cell |

Typically the manipulators used are Master Slave Manipulator(MSM : Model-8), Articulated Manipulator (AM-11) , Rugged Duty Manipulator (RDM), Extended Reach Manipulator (ERM), Three Piece Manipulator (TPM) and Power Manipulator (PM). The Servo Manipulators are the advanced version of the manipulators where a closed loop of position, velocity and the force is done on real time to exactly simulate the slave side environment on the master. This makes the operator to have a real feel of the slave environment, particularly feel of the force exerted at the end effecter. IGCAR, Kalpakkam has recently developed a force sensing and feedback Servo Manipulator (SM), for use in remote handling tasks. By virtue of the use of servo controls through the electric cables, the SM generally has master and slaves separated only by cables. This paper discussed about the kinematic synthesis and close loop control of the servo manipulator. Further in order to reflect the force in the master arm from the slave environment; the servo digital amplifiers are networked to read the joint motor torques and the joint motor positions. This paper also details the construction of the manipulator Jacobian in real time which is pose dependant. From the Jacobian inverse, the joint torques is converted to the manipulator force. This incorporates acceleration forces, centripetal forces and the Coriolis forces also. The methodology is programmed into the Servo Manipulator control system and tested. All joints and the gripper on slave arm are electrically driven. The movement of master arm is iso kinematically coupled to the slave arm and is provided with the necessary sensors for master-slave operations. There is no mechanical linkage between master and slave arm and are connected only by electric cables and communication cables. The arms are connected by two way communication cable with controller. Master arm may be operated in front of the hot cell or from a control room to perform the tasks in the slave environment.

## 2. MANIPULATORS FOR THE USE IN HOT CELLS

Master Slave Manipulators (MSMs) are the most dexterous general-purpose remote handling tools in Hot cells as shown in fig.2. An MSM has two arms: a master arm in the operating area and a slave arm inside the hot cell. When the human operator holds and manipulates the master arm, the slave arms and the gripper in slave arm reproduces the motion of the master arm along with the handgrip in the master arm. Based on the mechanical power source, MSMs are classified as mechanical manipulators and servo manipulators: mechanical manipulators use the power of the human operator translating to the slave environment through direct mechanical links, whereas the servo manipulators use electric or hydraulic actuators.

## A. Mechanical Manipulators

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| C:\Users\DEEPAK KUMAR\Desktop\servo manipulator\Master-Slave Manipulator A112.png  Slave arm  Master arm |
| FIG.2 Mechanical Manipulator |

In a mechanical manipulator, the master arm and the slave arm are connected by a through-tube. The motions generated by the operator on the master arm are mechanically transmitted to the slave arm, through the linkages in the master arm, the through-tube and the slave arm. Wire ropes, tapes and chains are used in the Articulated Manipulator models, whereas the models like MSM, Extended Reach Manipulator (ERM), and Three-Piece Manipulator (TPM) for power transmission between the master and the slave arms. It has more dexterity by limited approach as it is a fixed manipulator.

## B. Power Manipulators (PM)

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| FIG.3 Power Manipulator |

PM is a electrically switch operated manipulator as shown in fig.3. It does not have master arm. Hence there is no force and position feedback. Generally PM is fixed in transporter (Gantry) used for lifting and transferring of heavy load at large volume. It has very low dexterity. But PM has a good power multiplier, which is often configurable to scale up the mechanical power from the master to the slave.

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| FIG.4 CAD model of Servo Manipulator |

## C. Servo Manipulators(SM)

In the servo manipulator, there is no mechanical linkage between the master arm and the slave arm. They are connected through two way communication cables through a central controller. Generally slave arm is mounted on a transporter in the hot cell, giving large effective work volume. In hot cells, a single SM can replace the combination of multiple MSM & PM and also SM has an additional important user friendly feature, i.e. slave arm can be moved using jog mode by operation of joy stick or push button without movement of master arm. Slave arm can be used as a serial robotic arm for repeated operation to the defined coordinate in the hot cell space by teach mode through computer. All the joints of slave arm will be moved simultaneously and the force and position values will be stored in the computer for the smooth operation. Figure.4 shows the CAD model of the developed Servo Manipulator. The force reflecting tele robot represents a new generation of remote handling manipulator, with advanced features like position control of the slave arm in world coordinates, indexing in world coordinates, scaling of slave motion, teach & playback and interactive robot control.

## 3. KINEMATIC DESIGN OF SERVO MANIPULATOR

Typically a combination of 3 revolute joints give much articulating to the manipulator and the wrist axes is typically 3 for orientations which generally intersects. Such cases are easy to handle mathematically through a kinematic decoupling method and solve the Inverse Kinematics (IK) only for the global 3R and solve the oriental axes through a Euler rotation matrix. Figure.5 shows the kinematic model of the servo manipulator. Figure.6 shows the schematic of Servo Manipulator that clearly describes the Denavit-Hartenberg parameter which will be used for the construction of the Jacobian matrices for kinematic and force synthesis. In order to have the maximum dexterity, one pair of arms is used in the construction of the servo manipulator. Table.1 shows the DH parameters for one set of arms forming the left arm of the Servo Manipulator. The same with the base orientation change is adapted for the other arm i.e. the right arm.

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| FIG.5 Kinematic model of Servo Manipulator | FIG.6 Schematic of slave side Servo Manipulator |

## 3.1 DH Parameter for Servo Manipulator

A robot manipulator consists of several links connected by single degree of freedom joints namely , a revolute or a prismatic joint. In order to control the end-effecter with respect to the base, it is necessary to find the relation between the coordinate frames attached to the end-effecter and the base. This can be obtained from the description of the coordinate transformations between the coordinate frames attached to all the links and forming the overall description in a recursive manner.

As a first step, a systematic general method is to be derived to define the relative position and orientation of two consecutive links. The problem is to define two frames attached to two successive links and compute the coordinate transformation between them as shown in fig.7a.

1. Let axis i denotes the axis of the joint connecting link i −1 to link i.
2. A coordinate system Xi, Yi, Zi is attached to the end of the link i −1 not to the link i for i = 1 . . . n+1.
3. Choose axis Zi along the axis of joint i, whose positive direction can be taken towards either direction of the axis.
4. Locate the origin, Oi, at the intersection of axis Zi with the common normal to Zi−1 and Zi. Also, locate O′i on Zi at the intersection of the common normal to Zi and Zi+ 1.
5. Choose axis Xi along the common normal to axes Zi−1 and Zi with the direction from former to the later.
6. Choose axis Yi so as to complete a right handed frame.

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| FIG 7a: DH parameter of a serial robot |

The four DH parameters are defined as follows:

* di (Joint offset)
* θi (Joint angle)
* αi (twist angle)
* ai (Link length)

Parameters, di and θi, are, variables depends on the type of joints in use. In particular,

* θi is variable if joint i is revolute; and
* di is variable if joint i is prismatic.

So, for a given type of joint, i.e., revolute or prismatic, one of the DH parameters is variable, which is called 'joint variable,' whereas the other three remaining parameters are constant that are called 'link parameters. DH parameters of servo manipulator are shown in Table 1.

Table 1 DH parameter of servo manipulator

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| SL No | Link | a(Link Length) |  |  | d (joint distance) |
| 1 | Link 1 | 0 | 96 |  | 0 |
| 2 | Link 2 | 400 | 0 |  | 170 |
| 3 | Link 3 | 0 | 90 |  | 0 |
| 4 | Link 4 | 0 | -90 |  | 520 |
| 5 | Link 5 | 0 | 90 |  | 0 |

## 3.1 BASIC TRANSFORMATION BETWEEN COORDINATE FRAMES FOR THE SERVO MANIPULATOR

Generally Transformation matrix between any two joints is given below as shown in fig.7b;

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|  |
| FIG.7b Transformation matrix between two joint |

n-1Tn = (1)

Equation (1) shows the transformation between any two joint coordinate frames. Similarly the transformation of the end effecter to the global coordinates is the multiplication of all the joint transformations and is as below in Equation (2);

0T6 = 0T1  1T2 2T3  3T4 4T5 5T6 (2)

## 3.2 FORWARD AND INVERSE KINEMATICS

The forward kinematics shows the end effecter as a function of joint space variables and shown in the below Equation (3);

(3)

Inverse Kinematic equation is as in Equation (4);

(4)

The Jacobian is a good way to linearise a nonlinear problem here in this case transforming the joint space motion to the global space using a discrete approach. The column vectors represent the end effecter coordinate transformation with respect to the joint space change. The following Equation (5) represents the Jacobian matrix.

]= (5)

Computing the Jacobian is the complex part where one has to arrive at the Jacobian generating vectors from the basic transformation matrices. The following section describes the formulation of the Jacobian matrix from the Jacobian generating vectors for the Servo Manipulator.

## 3.3 JACOBIAN GENERATING VECTORS

The forward velocity kinematics of a robot solves the problem of relating joint speed θ' to the end-effecter speeds. The joint speed θ' of an n DOF robot is a nx1 vector.

From forward positional kinematics

δX = J(θ) \* δθ (6)

Taking the first derivative of equation (6)

V = J(θ) \* θ' (7)

Where J(θ) is a Jacobian matrix.

The Jacobian J constructor for n axis manipulator can be represented by Equation (8);

(8)

...

Jacobian (J )can be calculated column by column. In general the Jacobian generating vector for the ith column of J is denoted by .The Equation (9) shows the generalized Jacobian generating vector.

(9)

From the above relations Jacobian generating vectors for servo manipulator for the given DH parameter can be found

Table 2 Nomenclature

|  |  |
| --- | --- |
|  | Axis as seen from global frame of reference |
|  | End effector coordinate with respect i-1 frame as seen from global frame of reference |

## 3.3 JACOBIAN GENERATING VECTORS FOR SERVO MANIPULATORS

The Jacobian matrix of a 6 DOF articulated robot is a 6 \* 6 matrix. The robot was shown in Figure 6.

The ith column of the Jacobian, (q), is

(q) = (10)

For the first column of the Jacobian matrix, it is required to find and . The direction of the - axis in the base coordinate frame is

= (11)

And the position vector of the end-effector frame is . Which can be directly determined from the fourth column of the transformation matrix, ,

=

(12)

which is

(13)

where

Therefore,

And the first Jacobian generating vector is:

(14)

For the 2nd column we need to find and The in the base frame can be found by

(15)

The first half of is The vector is the position of the end-effector in the coordinate frame, however it must be expressed in the base frame to be able to perform the cross product. An easier method is to find and transform the resultant into the base frame. The vector is the fourth column of which, is equal to

Therefore, the first half of is

and is:

(16)

The 3rd column is made by and the vector is position of the end-effector in the coordinate frame and is the fourth column of The in the base frame can be found by

And the cross product can be found by transforming the resultant of into the base coordinate frame.

Therefore, is:

(17)

The 4th column needs The vector can be found by transforming to the base frame

And the first half of can be found be calculating and transforming the resultant into the base coordinate frame.

Therefore, is:

(18)

The 5th column needs we can find the vector by transforming to the base frame.

The first half of is expressed in the base coordinate frame.

Therefore, is:

(19)

The 6th column is found by calculating The vector is

And the first half of expressed in the base coordinate frame.

Therefore, is

(20)

And the Jacobian matrix for the articulated robot calculated

## 4. MANIPULATOR FORCE ESTIMATION FROM THE JOINT TORQUES

Work done by the manipulator in the task space is the total work done by the manipulator in the joint space. This gives the following equation;

(21)

This can be written as;

(22)

From inverse kinematic small change in Cartesian space can be related to angular space by following equation

(23)

Substituting δx into equation (22)

(24)

(25)

Taking transpose on both the side

(26)

(27)

The force computed from the Equation (27) represents the manipulator force. These forces is computed from the motor torques and thus represent the complete force which incorporates payload, inertial force, friction in the joint, Coriolis force and the gravity force on the manipulator. This force is computed in real time by sensing the joint actuator torques from each axis of the manipulator.

## 5. DISTRIBUTED CONTROL SYSTEM (DCS) FOR SERVO MANIPULATOR

The digital servo drives are networked through a industrial standard bus based communication protocol Ether CAT. A computing system PC is added to the network do the kinematic and force synthesis real time. A program is made in Visual Dot net C++ with the Application Program Interface drivers provided by the digital servo driver vendor. The Figure.8 & 9 shows the abstraction of the manipulator force computation in real time from the joint axis actuator torques. The digital servo drives are networked through the Ether CAT bus and the computation PC attached to the same bus will scan the joint actuator torques. For each time step, the joint actuator encoder readings are read and the Jacobian matrix is computed in real time. The equations in the section 3.3 are used to compute the Jacobian matrix. Fig.9 shows the distributed control architecture and Ether Cat bus for networking & the servo drive control.

Compute Jacobian J (Ɵ)

Read Joint actuator torques (ζ) from motor current

Forward Kinematics  
 e=f (Ɵ)

Read Joint encoder values and computes angles

Compute Fx, Fy and Fz

Fig. 8 flow chart of numerical calculation of servo manipulator

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| FIG.9 Distributed Control System for Servo Manipulator |

## 6. TESTING OF SERVO MANIPULATOR

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| FIG.10 Test layout showing the master and slave for the force measurement. |

In order to check the position synchronization, the master is moved in the definite axis direction and the slave is measured for the movement in the same axis movements. The synchronization is good and found to have a very good repeatability. As the master side the force is simulated only on the vertical axis, the force Fy computed in real time is applied on the master side through the motors run on the torque modes. In order to sense the master side force on the arm, the motor is attached with a pulley and a steel rope in which a spring balance is attached. The load sensor reads the load on the master side. The gripper side is also fixed with strain gages which when the arm in extended condition will directly read the loads. The Figure 10 shows Test layout showing the master and slave for the force measurement.

## 7. RESULTS

The algorithm discussed in section 5.0 was coded in Visual Dot net C++ force is sensed in four orientations and are listed in table 3. It can be easily concluded from fig.11 that operator will have feel of slave environment

Table.3 Reflected force on the master arm

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Weight added in gripper (kg) | Reflected force in master (Kg) @ 4 orientations | | | |
| 0 | 90 | 180 | 370 |
| 0 | - | - | - | - |
| 1 | 0.95 | 0.9 | 0.8 | 0.4 |
| 2 | 1.9 | 1.95 | 1.65 | 0.85 |
| 3 | 2.9 | 3 | 2.55 | 1.3 |
| 4 | 3.95 | 4 | 3.45 | 1.9 |
| 5 | 4.95 | 5.15 | 4.45 | 2.3 |
| 6 | 6 | 6.15 | 5.5 | 2.95 |
| 7 | 7 | 7.25 | 6.4 | 3.45 |
| 8 | 8.1 | 8.45 | 7.2 | 4.05 |
| 9 | 9.15 | 9.6 | 8 | 4.65 |
| 10 | 9.9 | 10.6 | 8.9 | 5.25 |
| 11 | 10.9 | 11.5 | 10 | 5.6 |
| 12 | 11.75 | 12.5 | 11.2 | 6.05 |
| 13 | 12.7 | 13.8 | 11.9 | 6.95 |
| 14 | 13.75 | 15.1 | 12.7 | 7.75 |
| 15 | 14.95 | 16.3 | 14 | 8 |

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| FIG.11 Reflected force measurement on the master |

## 8. CONCLUSION

A 15 Kg Servo Manipulator has been designed and fabricated for the remote handling applications. An iso kinematic designing has been done to have a similar master and slave arms. A pair of master arms and a pair of slave arms are designed and fabricated. The arm joint actuators are fixed with very low backlash error actuators and also with high resolution encoders/resolvers for the accurate link angle measurements. The servo drives are networked using the Industrial standard EtherCAT bus. A force synthesis has been performed I real time to use encoder angles to construct the Jacobians and the motor torques for the force synthesis of manipulator. This has been listed in real time and found to give good results.

REFERENCES

1. 1. Jong Kwang Lee,Byung Suk Park, Kiho Kim, Ho Dong Kim, “Design and Fabrication of a Servo-manipulator for Use in the PRIDE Facility, Proceedings of 2009 IEEE International Symposium on Assembly and Manufacturing 17-20 November2009, Suwon, Korea.
2. 2. M.N. Rao et al, “A Customized Servo Manipulator for Remote Handling in Nuclear Facilities”, Advancement in Automation, Robotics and sensing, 2016
3. 3. Reza M. Jazar, “Theory of Applied Robotics: Kinematics, Dynamics, and Control”, 2nd Edition, Springer, 2010.