Force estimation and feed back control of the Servo Manipulator for the remote handling use in Hot Cells

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CATEGORIES OF MANIPULATOR & USE OF MANIPULATOR IN HOTCELL

Articulated manipulators

Telescopic manipulators

Extended reach Telescopic manipulator

CATEGORIES OF MANIPULATOR & USE OF MANIPULATOR IN HOTCELL


3.2 electrical master-slave manipulator
manipulator reproducing the movements of the hand and arm of the operator by means of isokinematic master and slave arms with bilateral electrical position control (force reflection)

Note 1 to entry: The word “bilateral” refers to the property of the system to be indifferently moved by acting on the master arm or on the slave arm.

Note 2 to entry: The slave arm is generally mounted on a transporter (mobile).

Servo manipulator
• Operator gets a real feel of slave side
• Gantry mount makes extended work volume in the cell
• Iso-kinematic system
Servo Manipulator - Parameters

- Payload capacity: 15 kg
- Degrees of freedom: 10
- Cross Travel: 1200 mm
- Z - Axis: 425 mm
- Azimuth: ±170°
- Base rotation: ±45°
- Shoulder elevation: +60°/ - 90°
- Elbow elevation: +90°/- 45°
- Elbow rotation: ±170°
- Wrist rotation: ±170°
- Wrist elevation: +120° / - 45°
- Gripper opening: 90 mm
DESCRIPTION OF SERVO MANIPULATOR (SM)

• Modular design for easy mounting on Gantry
• Redundancy on DOF for dexterity
• Networked controller for synchronous motions
• Master-slave interconnected only through cables and no direct mechanical links – master can be conveniently placed in any desired location and slave work volume increased through Gantry mounts
• Real time Jacobian matrix computation and joint torques converted to manipulator forces
• Hard master slave synchronization through joint axis servo drives (low latency)
• 30% work volume overlap for both arms – Good performance of both arm interactive tasks
KINEMATIC MODEL OF SERVO MANIPULATOR

\[ J = \frac{df}{dx} = \left[ \begin{array}{c} \frac{\partial f}{\partial x_1} \\ \vdots \\ \frac{\partial f}{\partial x_n} \end{array} \right] = \left[ \begin{array}{cc} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_m}{\partial x_1} & \cdots & \frac{\partial f_m}{\partial x_n} \end{array} \right] \]

Forward kinematics:
\[ \delta e = J \delta \theta \]

Inverse Kinematicis:
\[ \delta \theta = J^{-1}[\delta e] \]

DH parameter
\( a_i \) – Link length
\( \alpha_i \) – Link twist
\( \theta_i \) – Joint angle
\( d_i \) – Joint z axis distance
Joint motor velocity to manipulator end effector velocity
Differentiating the Kinematic equation we get,

\[ \dot{\mathbf{x}} = J \dot{\mathbf{\theta}} \]

Jacobian is a linear transformation, mapping joint speed to Cartesian speed

In this case J has been generated column by column; \( i^{th} \) column of Jacobian Matrix is

\[
c_i(q) = \begin{bmatrix}
0 \mathbf{k}_{i-1} \times & 0 \mathbf{d}_n
\end{bmatrix}
\]

\[
\begin{bmatrix}
\dot{X} \\
\dot{Y} \\
\dot{Z} \\
\dot{\phi}_x \\
\dot{\phi}_y \\
\dot{\phi}_z
\end{bmatrix} = \begin{bmatrix}
\dot{\theta}_1 \\
\dot{\theta}_2 \\
\dot{\theta}_3 \\
\vdots \\
\dot{\theta}_n
\end{bmatrix}
\]
Total manipulator work done in task space = manipulator work done in tooltip space.

\[ F^T \delta X = \tau^T \delta \theta \]

\[ \delta X = J . \delta \theta \]

\[ F^T J . \delta \theta = \tau^T \delta \theta \]

\[ F^T J = \tau^T \]

\[ J^T . F = \tau \]

\[ F = (J^T)^{-1} \cdot \tau \]

The state variables \( \theta, \dot{\theta}, \ddot{\theta} \) are measurable through rotary encoders.

Dynamic analysis using LaGrange equation

\[ \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}} \right) - \left( \frac{\partial L}{\partial q} \right) = Q \]

Where Lagrangian \( L=T-V \)

\( T \) - Kinetic energy of the system

\( V \) - Potential energy of the system

\[ M(\ddot{\theta}) + C(\theta, \dot{\theta}) + G(\theta) = \tau \]

Forces in the system

- payload,
- inertial force,
- friction in the joint,
- Coriolis force
- Gravity force on the manipulator
CONTROL LAYOUT OF SERVO MANIPULATOR

MASTER ARM

LEFT ARM
- Shoulder Rotation
- Shoulder Elevation
- Elbow Rotation
- Elbow Elev
- Wrist Rotation
- Wrist Elev
- Gripper

RIGHT ARM
- Shoulder Rotation
- Shoulder Elevation
- Elbow Rotation
- Elbow Elev
- Wrist Rotation
- Wrist Elev
- Gripper

EtherCAT Communication BUS

Cross Travel
- Azimuth
- Vertical
- Gantry

EtherCAT Communication BUS

SLAVE ARM

Control Panel
PC
MASTER SLAVE POSITIONAL FEEDBACK

- Mater side joint angle sensed and compared with slave axis. The difference is applied as slave motion command
- Drive level programming done to reduce latency
- The slave joint parameters like pulse per revolution (PPR) and Gear Radios are all pre-programmed into the respective joint axis servo drives
- Periodic synchronization trigger at drive level to do corrections even when there is an out of synchronization between master-slave during a power failure.

Master-slave positional synchronization
In the present study only the vertical component force $F_y$ is applied on the master.

Slave arm loaded with known forces and the reflected force in the master measured and compared.

**Equation**: 

$$F = (J^T)^{-1} \cdot \tau$$

$$\begin{bmatrix} F_X \\ F_Y \\ F_Z \\ M_X \\ M_Y \\ M_Z \end{bmatrix} = (J^T)^{-1} \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \vdots \\ \vdots \\ \tau_n \end{bmatrix}$$

**Diagram**: EtherCAT Bus connecting all slave servo Drives.

**Process**: Compute Absolute angle (use PPR&GR), Compute Manipulator Jacobian, Compute the corresponding joint torques in master.

**Steps**: Joint Axis Encoder Position, Joint Axis Motor Current, Joint Axis Torque, Manipulator End effector force.
Table 2: Reflected force on the master arm

<table>
<thead>
<tr>
<th>Weight added in gripper (kg)</th>
<th>Reflected force in master (Kg) @ 4 orientations</th>
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<tr>
<td></td>
<td>0°</td>
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<td>15</td>
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</table>

Figure 6: Reflected force measurement on the master
SERVO MANIPULATOR – MASTER & SLAVE

Master

Slave
• Modular design of servo manipulator
• Real time Jacobian matrix computation to translate parameters back and forth between joint space and end effector space
• Joint space motor currents used to compute manipulator force
• Gantry mount design makes it flexible to be mounted for large task space applications
• Force limiting for applications that demand soft/tender handling


Thank You