Fault Tolerance Design for Servo Manipulator System Operating in a Hot Cell

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Abstract: In this paper, fault tolerant mechanisms are presented for a servo manipulator system designed to operate in a hot cell. A hot cell is a sealed and shielded room to handle radioactive materials, and it is dangerous for people to work in the hot cell. So, remote operations are necessary to handle radioactive materials in the hot cell. KAERI has developed a servo manipulator system to perform such remote operations. However, since electric components such as servo motors are weak to radiations, fault tolerant mechanisms have to be considered. For fault tolerance of the servo manipulator system, hardware and software redundancy have been considered. In case of hardware, radioactive resistant electric components such as cables and connectors have been adopted and motors driving a transport have been duplicated. In case of software, a reconfiguration algorithm accommodating one motor's failure has been developed. The algorithm uses redundant axis to recover the end effector's motion in spite of one motor's failure.

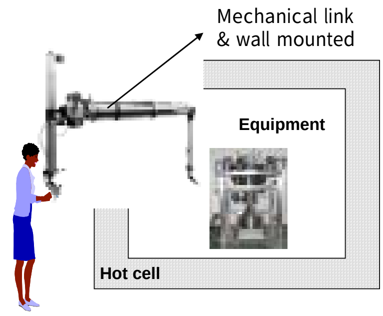
Keywords: Fault tolerant design, servo manipulator system, hot cell, redundancy, reconfiguration.

1. INTRODUCTION

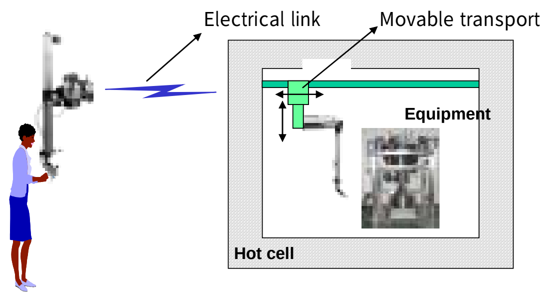
A hot cell is a radiation shielded room where radioactive materials are treated. It is a very useful facility to treat radioactive materials. Mechanical master-slave manipulators (MSMs) are used to remotely handle or treat radioactive materials and equipment inside a hot cell because human operators cannot handle directly. MSMs are very useful, so those are necessary equipment for a hot cell operation. However, since those are wall mounted, work scopes of MSMs are limited. So, different type's manipulators, electric servo manipulators, have been developed to overcome limited work scopes. In case of a servo manipulator, the slave arm inside a hot cell is connected by electric wires to the master arm outside a hot cell, so the slave arm is driven by servo motors and is composed of several electric components.

However, since electric components are very weak to radiation, unexpected faults related with motors or electric components may occur. In case of MSMs, since all parts exposed to radiation are mechanical components such as rod, pulley, steel wire, etc., MSMs are more fault tolerant than electric servo manipulators. So, a reliable servo is required for a hot cell operation.

We(KAERI) have developed a servo manipulator operating in a hot cell where high level radioactive materials are treated. A transport system similar to a crane is used to move the servo manipulator to arbitrary positions. In this paper, fault tolerant designs adopted for the servo manipulator are presented. Hardware and software designs have been considered. A numerical example is presented to show that the reconfiguration algorithm can accommodate one motor's failure as a software design. The concepts and designs presented here are useful to design reliable manipulators operating in hazardous regions.



(a) The working concept with a conventional MSM



(b) The working concept with a servo manipulator

Fig.1 Comparison of an MSM and a servo manipulator

2. SYSTEM DESCRIPTION

The developed servo manipulator system consists of a transport system, a slave manipulator, a master manipulator, and a control system.

The transport system moves the slave manipulator in a hot cell. A girder and a trolley move in the X-Y plane, and a telescopic tube raises or lowers the slave arm(the Z motion). The driving sources are servo motors.

The slave manipulator is driven by servo motors, and the master manipulator has the same configuration with the slave one. The master one is an input device commanding the slave one's position or configuration.

The slave manipulator and transport system will be installed in a hot cell. In the hot cell, high-level radioactive materials are placed. In general, electronic equipment is very weak to high-level radiations.[1-2] Radiations decrease the estimated life time of electronic equipment. Damaged components can not perform their desired motions, i.e., fail. So, we have to consider fault tolerance of the servo manipulator system. The next section shows fault tolerant designs considered.

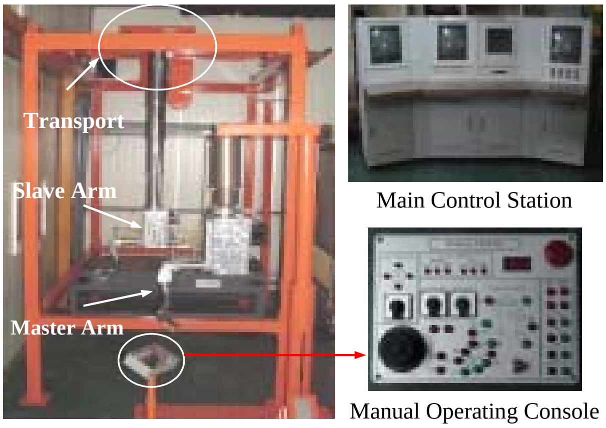


Fig.2 The developed servo manipulator system

3. FAULT TOLERANCE DESIGN

3.1 Hardware

The electronic components of the slave manipulator are the followings :

- Servo motors
- Signal and power cables
- Connectors

For servo motors, resolver type servomotors have been adopted. Encoder type motors are not used in a hot cell since encoders are weak to radiation. Resolver type motors are generally used in a harsh environment. Resolver type motors are expected to run for a longer time than encoder type motors. Also, the servo motors are designed to be easily replaced for fault cases.

For signal and power cables, radioactive resistant cables have been selected. The selected cables can endure up to 10^8 rad. The estimated absorbed dose is 6.7×10^4 rad during the planned operating time. So, the cables will be normal. The selected connectors are also radioactive resistant and can endure up to 10^8 rad.

The transport is placed in the upper part of the hot cell. It is difficult to repair the transport components. Since radiation decreases as the distance increases, the effect of radiation will be decreases too. However, because MSMs can not reach the transport, the maintenance will be difficult and reliability of the transport is also important. The followings are the electric components of the transport :

- Servo motors
- Signal and power cables
- Connectors

The cables and connectors are the same ones as the slave manipulator's. The servo motors have been duplicated with two resolver type motors. Duplication of components is a general design method to increase reliability, i.e., fault tolerance. Two motors share the same axis as Figure 3.

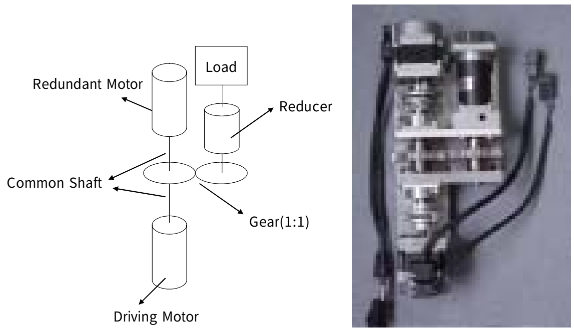


Fig. 3 Duplication of driving motors

3.2 Software

Software fault tolerant design means a reconfiguration algorithm for the slave manipulator. The objective of reconfiguration is temporary fault accommodation in case of a motor's fault. In practice, if one motor of the slave manipulator is faulty, the slave manipulator is decontaminated and the faulty motor is replaced by a normal one. However, the maintenance process may take time. So, if a task to be done is simple and urgent, the slave manipulator has to operate after reconfiguration.

In this paper, we have considered a reconfiguration algorithm proper to the servo manipulator for teleoperation. Fault tolerance for the industrial manipulators has been greatly studied.[3-5]

Teleoperation is different to general position control of a manipulator in that a human operator is a major control source. It means that the error exact position command following is not significantly important and a small position error between the slave and master manipulator is accommodated by the human operator. The operator does not compare the positions of the slave and master one, but compare the positions of the slave and target objects. If the end effector of the slave one does not reach a target object, the operator moves the master one a little more. But, the slave one has to move with proper speed and have proper degrees of freedom even after a fault occurs.

Figure 4 shows the schematic diagram of the developed servo manipulator system. The master and slave arm have the same configuration. The master is called a replica type. In that case, the control of the slave is very easy, since there is no need to solve inverse kinematics. Each joint's displacement angle of the master is the direct command to the slave joint. Force reflection is the same as the slave control. And, in normal operation, the transport is used only for moving the slave arm at operating positions.

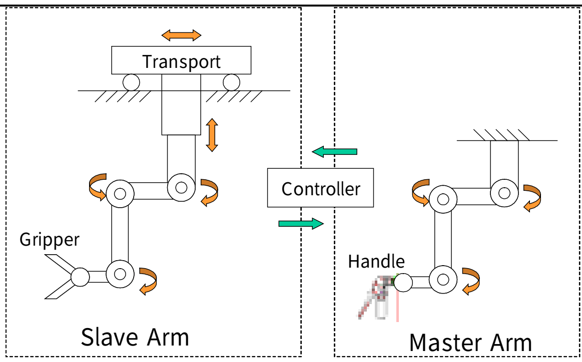


Fig.4 Schematic diagram of the servo manipulator

However, we assume a motor's failure for the slave. The replica type control is no longer available, and the universal type control is used, i.e., the joint-to-joint control does not hold but the motion of end effectors (handle and gripper) have to coincide with each other. As early mentioned, the teleoperation is monitored and controlled by a human operator, the exact coincidence of position or attitude is not severe, but the speed and d.o.fs have to coincide. In our case, the degree of freedoms of the transport is treated as redundant d.o.fs. It is assumed that a single motor's failure occurs and multiple failures do not occur.

Figure 5 shows the notations for the slave arm dynamics. 2D motions have been considered.

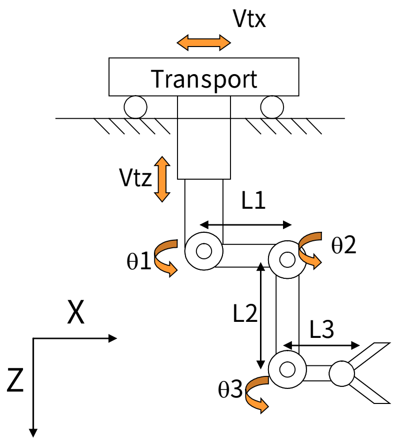


Fig.5 Notations of the slave arm dynamics

The end effector's position is :

$$
\begin{aligned}
x_e &= x_t + L_1 \cos\theta_1 + L_2 \sin(\theta_1+\theta_2) + L_3 \cos(\theta_1+\theta_2+\theta_3)\\
z_e &= z_t - L_1 \sin\theta_1 + L_2 \cos(\theta_1+\theta_2) - L_3 \sin(\theta_1+\theta_2+\theta_3) \quad (1)\\
\theta_e &= \theta_1+\theta_2+\theta_3
\end{aligned}
$$

then, the velocity is :

$$
\begin{aligned}
v_{xe} &= v_{xt} - \varpi_1 L_1 \sin\theta_1 + (\varpi_1+\varpi_2) L_2 \cos(\theta_1+\theta_2)\\
&\quad - (\varpi_1+\varpi_2+\varpi_3) L_3 \sin(\theta_1+\theta_2+\theta_3)\\
v_{ze} &= v_{zt} - \varpi_1 L_1 \cos\theta_1 - (\varpi_1+\varpi_2) L_2 \sin(\theta_1+\theta_2)\\
&\quad - (\varpi_1+\varpi_2+\varpi_3) L_3 \cos(\theta_1+\theta_2+\theta_3) \qquad (2)\\
\omega_e &= \omega_1+\omega_2+\omega_3
\end{aligned}
$$

It can be rewritten as :

$$V_E = A\Omega \qquad (3)$$

$$V_E = \begin{bmatrix} v_{xe} & v_{ze} & \varpi_e \end{bmatrix}^T, \quad \Omega = \begin{bmatrix} v_{xt} & v_{zt} & \varpi_1 & \varpi_2 & \varpi_3 \end{bmatrix}^T,$$

$$A = \begin{bmatrix} 1 & 0 & -L_1 s_1 + L_2 c_{12} - L_3 s_{123} & L_2 c_{12} - L_3 s_{123} & -L_3 s_{123} \\ 0 & 1 & -L_1 c_1 - L_2 s_{12} - L_3 c_{123} & -L_2 s_{12} - L_3 c_{123} & -L_3 c_{123} \\ 0 & 0 & 1 & 1 & 1 \end{bmatrix}$$

and $s_{ijk} = \sin(\theta_1+\theta_2+\theta_3)$, $c_{ijk} = \cos(\theta_1+\theta_2+\theta_3)$.

V_E is the desired speed and Ω is the control speed. When the master arm moves, the speed of the handle is the desired speed of the slave arm's gripper, and the control speed is properly coordinated to match the desired speed. The problem is defined as :

$$
\begin{aligned}
&\underset{\Omega}{\text{minimize}} \; J = \left\| V_E - A\Omega \right\| \\
&\text{subject to } \left|\Omega_i\right| < \Omega_{i,\max}
\end{aligned} \qquad (4)
$$

It is an optimization problem to find the proper control speed minimizing the velocity error and subject to speed limitation. A suboptimal solution may be the minimal norm solution as :

$$\Omega = A^+ V_E = A^T (AA^T)^{-1} V_E \qquad (5)$$

But each element of the control speed is limited, so the solution has to be scaled down as :

$$
\begin{aligned}
&\overline{\Omega} = \Omega / \alpha \\
&\alpha = \max_i \left(\left| \frac{|\Omega_i|}{\Omega_{i,\max}} \right| \right)
\end{aligned} \qquad (6)
$$

If $\alpha > 1$, the desired speed is not followed, i.e., $V_E \neq A\overline{\Omega}$. Such performance degradation may be inevitable. The speed limitation can be augmented as :

$$
\begin{aligned}
&V_E = AL\hat{\Omega} \\
&L = \operatorname{diag}\left(\left|\Omega_{i,\max}\right| \right),
\end{aligned} \qquad (7)
$$

The solution may be

$$\hat{\Omega} = (AL)^+ V_E = (AL)^T (ALL^T A^T)^{-1} V_E \qquad (8)$$

and the scale factor may be

$$\alpha = \max_i \left(\left|\Omega_i\right| \right) \qquad (9)$$

In case of motor's failure, the faulty joint is locked, and the corresponding column of the matrix A is omitted, and Eq.(5)

or (8) is applied to the faulty system. Eq.(4), (5), and (8) has to be solved continuously, but Eq.(5) and (8) can also be applied to the vicinity of the reference position because the matrices A^+ and $(AL)^+$ are numerically similar in the vicinity of the reference position. This is advantageous because the computation is not much. If the position deviates from the reference position, the matrices have to be recalculated.

The reconfiguration procedure can be summarized as :

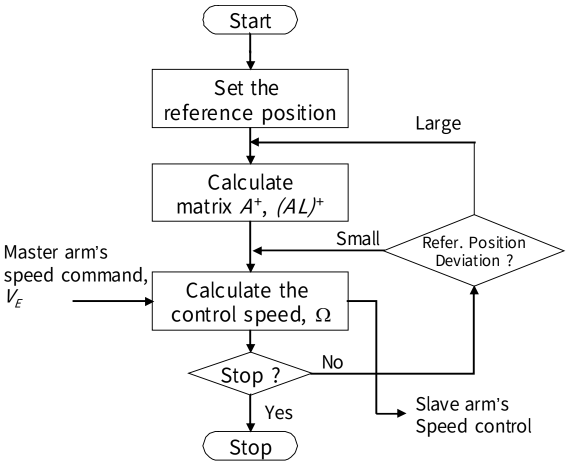


Fig.6 Reconfiguration procedure.

Figure 6 is the procedure for Eq.(5) and (8). If Eq.(4) is used, the recalculation of the matrices A^+ and $(AL)^+$ is unnecessary and the continuous optimization has to be done.

4. SIMULATION EXAMPLE

The numerical specification of the servo manipulator of KAERI is :

Table 1. Numerical data for the servo manipulator.

Parameters	Values	Dimension
L_1, L_2, L_3	0.3, 0.3, 0.25	m
Max. v_{xt}, v_{zt}	0.13, 0.1	m/sec
Max. ϖ_1, ϖ_2, ϖ_3	2.5, 2.5, 6.9	rad/sec
Reference θ_1, θ_2, θ_3	0.0, 0.0, 0.0	rad

Example 1.

Axis 2 has been assumed locked at the reference position. Several arbitrary desired velocity have been given, and control speeds and error have been calculated by using Eq.(4), (5), and (8).

V_E	V by Eq.(4)	V by Eq.(5)	V by Eq.(8)
0.3, 0.1, 0.7	0.13,-0.07,0.66	0.08,0.03,0.19	0.11,0.04, 0.25
0.3,0.1,-0.7	0.3,0.1,-0.7	0.1,0.03,-0.24	0.27,0.09,-0.63
0.3,-0.1,0.7	0.23,-0.17,0.68	0.17,-0.06,0.39	0.17,-0.06,0.39
0.3,-0.1,-0.7	0.3,-0.1,-0.7	0.09,-0.03,-0.20	0.3,-0.1,-0.7
-0.3,0.1,0.7	-0.3,0.1,0.7	-0.26,0.1,-0.14	-0.3,0.1,0.7
-0.3,0.1,-0.7	-0.23,0.17,-0.68	-0.17,0.06,-0.39	-0.17,0.06,-0.39
-0.3,-0.1,0.7	-0.3,-0.1,0.7	-0.1,-0.03,0.24	-0.27,-0.1,0.63
-0.3,-0.1,-0.7	-0.13,0.07,-0.66	-0.08,-0.03,-0.19	-0.11,-0.04,-0.25

For some desired velocity, the proposed reconfiguration algorithm does well. Even though the performance degradation is inevitable, the proposed algorithm is thought to be a temporary fault accommodation.

5. CONCLUSION

Fault tolerant design has been presented for the servo manipulator developed by KAERI. Hardware and software designs have been considered. For hardware, radioactive resistant components and duplication have been used, and simple and easy reconfiguration algorithm has been for software design. These design efforts are useful and effective to increase the reliability of the servo manipulator operating in a radioactive region. The manipulator is going to be installed in a hot cell.

ACKNOWLEDGMENTS

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