Developing of Tele-Manipulation system for compensates time delay

System and Control lab.
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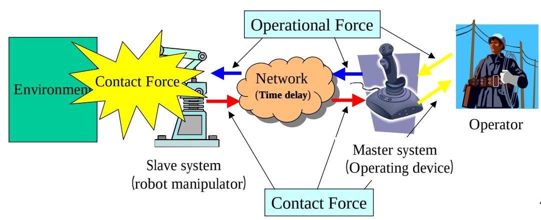
Motivation (Early studies)

(ⅰ) The design method using the passivity proposed by Anderson et al. And Extended by Niemeyer et al.
(ⅱ) The design method using robust control proposed by Leung et al. The method considers information delay to perturbation
(ⅲ) The design method using simple PD control proposed by Oboe et al.
(ⅳ)Predictive display of slave system environment with computer graphics.

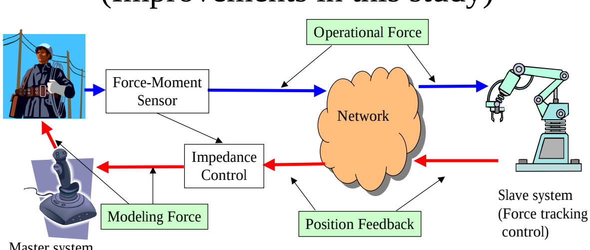
The system proposed until now is not achieve both stability and operatability.

Motivation (Technical issue)

A force feedback loop under time delay is major factor that makes the system unstable.
In order to guarantee the stability and the operatability, it is better not to include the force feedback with time delay.



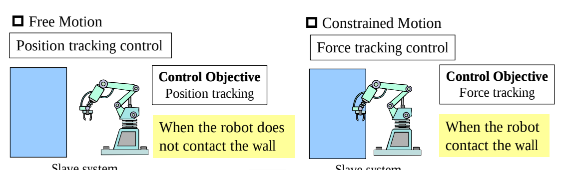
Motivation (Improvements in this study)



There is no force feedback loop. And, the information between master system and slave system exchanged by operator. Moreover, the stability of the system is always stable.

Motivation (Improvements in this study)

Our propose method consists of two type of motion.

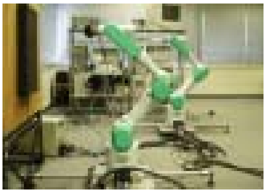


The method automatically switches two control law depending on contact situation. And, to achieve the control objectives in any cases.

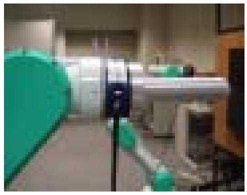
Control design
(Explanation of control law)

In this research, the operator operates the master manipulator using impedance control with operational force.

Mitsubishi Heavy Industry Ltd, PA-10



Master system consists of Force-Moment Sensor and handle.



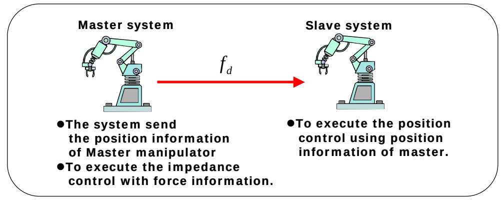
Master system

Control law of Free Motion

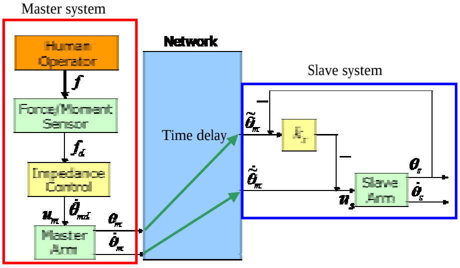
The feature of Free Motion

- Slave system does not be constrained by environment.
- There is no need to feedback the information of slave system to master system.

Control Processing



Block Diagram of Free Motion



f_d : Operation force θ_{md} : Desired angle

θ_m, θ_s : Present angle u_m, u_s : Control input

Control law of Free Motion

Master System

Impedance control without stiffness.

$$\frac{d}{dt}\begin{bmatrix} x_{m1} \\ x_{m2} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -d/m \end{bmatrix}\begin{bmatrix} x_{m1} \\ x_{m2} \end{bmatrix} + \begin{bmatrix} 0 \\ f_d/m \end{bmatrix}$$

$$\dot{\theta}_{md} = J^{-1}(\theta_m)\,\dot{x}_{md}$$

The system can fix at the state.

$$\dot{\theta}_m = u_m$$

$$u_m = \dot{\theta}_{md}$$

Control input of manipulator

Slave System

$$\dot{\theta}_s = u_s$$

$$u_s = \dot{\tilde{\theta}} - k_s(\tilde{\theta}_m - \theta_s)$$

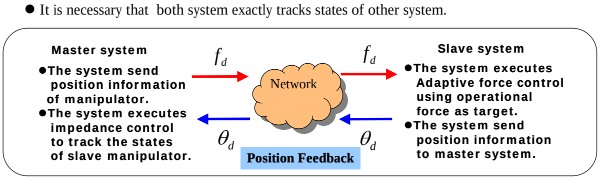
$x_{m1} = x_{md}$, $x_{m2} = \dot{x}_{md}$

x_{md} : Desired hand position

Control law of Constrained Motion

The feature of Constrained Motion

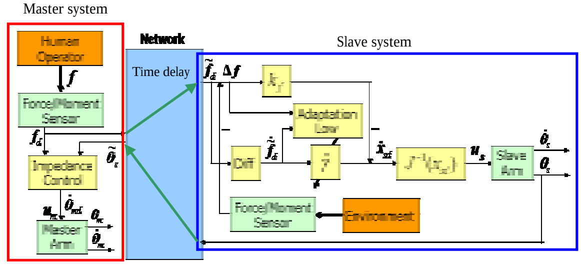
- It is necessary that the system transmit the contact force to operator.
- It is necessary that both system exactly tracks states of other system.



Our propose system does not feedback the force information. In addition, the system does not make force closed loop.

The system does not become unstable in any cases, and achieves good tracking performance.

Block diagram of Constrained Motion



Control law of Constrained Motion

Master System

Impedance control with stiffness.

$$\frac{d}{dt}\begin{bmatrix} x_{m1} \\ x_{m2} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -d/m \end{bmatrix}\begin{bmatrix} x_{m1} \\ x_{m2} \end{bmatrix} + \begin{bmatrix} 0 \\ f_d/m - k_{\hat{\gamma}}(\tilde{x}_s - x_m) \end{bmatrix}$$

$$u_m = \dot{\theta}_{md}$$

Control law of manipulator

Slave System

Adaptive force control

$$\dot{x}_{sd} = \hat{\gamma}(t)\dot{f}_d(t) - k_f \Delta f(t), k_f > 0.$$

$$u_s = J^{-1}(\theta_m)\dot{x}_{sd}.$$

$$(\dot{\hat{\gamma}} = -\alpha \dot{f}_d(t)\Delta f(t), \alpha > 0 : \textit{Adaptation law})$$

Jaydeep Roy, and Louis L. Whitcomb, 2002

Control law of Constrained Motion

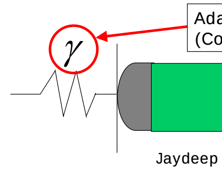
Adaptive Force Control

$$\dot{x} = \hat{\gamma}(t)\dot{f}_d(t) - k_f \Delta f(t), k_f > 0$$

$$u = J^{-1}(\theta_m)\dot{x}$$

$$(\dot{\hat{\gamma}} = -\alpha \dot{f}_d(t)\Delta f(t), \alpha > 0 : \textit{Adaptation law})$$

Adaptation parameter
(Compliance of environment)



Jaydeep Roy, and Louis L. Whitcomb, 2002

Stability of switching law

Parameter of Impedance control

$$2\left(\frac{d}{m}\right)^2 - k_{\hat{\gamma}} > 0$$

Parameter of Impedance control
for tracking

Experiment

For testing the performance of control law, we execute three cases of experiment.

① Testing of performance for Free Motion.

② Testing of performance for Constrained Motion.

③ Testing of stability for switching control law.

Experiment

① Testing of performance for Free Motion

Control purpose

・Positions between Master system and Slave system should be tracked.

Testing method

・To operate the system back and forth.

・To check system performance, we compared positions of both systems.

② Testing of performance for Constrained Motion

Control purpose

・States (positions and forces) between Master system and Slave system should be tracked.

Testing method

・Constant force Input for Master system.

・Varying force Input for Master system.

・To check system performance, we compared positions and forces of both systems.

Experiment

③Testing of stability for switching control law

Control purpose

・The system should not be unstable.

Testing method

・Touch and release the wall some time (Switching control law some time).

・Varying force Input for Master system.

・To check the system stable or not, we compared states of both system.

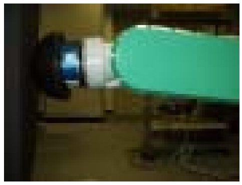
Experiment

① Push the wall attached sponge using slave system.
Then, robot manipulator is controlled for 1-DoF Motion.

② It has a 1 sec delay between Master system and Slave system on control software.

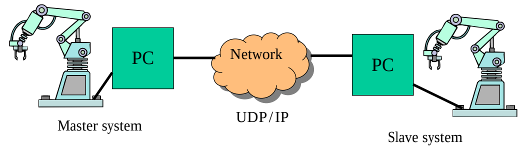
③ The data (forces and positions) are measured at Slave system side.

Slave system



Environment

- Master and slave manipulator are controlled by two PC.
- Communication between Master system and Slave system performed by UDP/IP.
- As control environment, we adopted Windows and Visual C++.NET for systems.



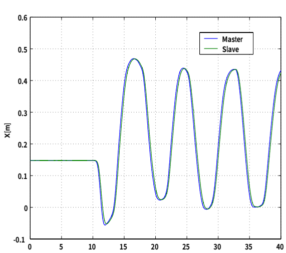
Environment

Experimental parameter

- $k_s = 0.1$
- m = 10, d = 100.
- α = 0.05.
- $k_f = 0.0005$
- $k_{\hat{\gamma}} = 50$ ($k_{\hat{\gamma}} < 200$)

Movie

Experimental result (Free Motion)

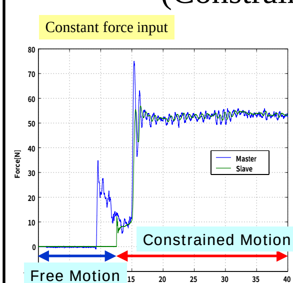


Position data

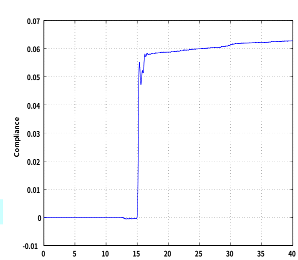
	Hand Position
Average of error	0.001
Variance of error	0.004

※Units: hand position [m]

Experimental result (Constrained Motion)



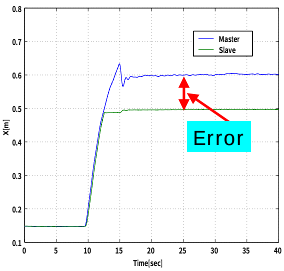
Force



Compliance

Experimental result (Constrained Motion)

Constant force input



Position

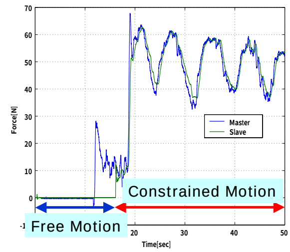
	Force	Hand position
Average of error	-0.308	0.104
Variance of error	2.059	2.602e-6

※1 Units: Force [N], Position [m]

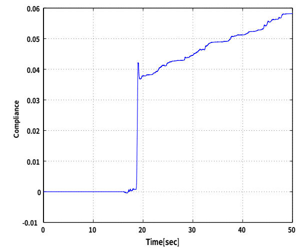
※2 Range of comparing data is 20[sec]〜40[sec]

Experimental result (Constrained Motion)

Varying force input



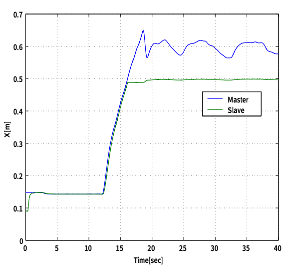
Force



Compliance

Experimental result (Constrained Motion)

Varying force input



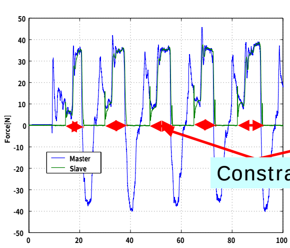
	Force	Hand Position
Average of error	-0.648	0.099
Variance of error	7.510	2.200e-4

※1 Units: Force [N], Position [m]

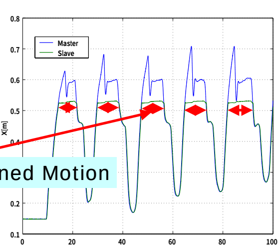
※2 Range of comparing data is 20[sec]〜50[sec]

Testing of stability for switching control law

Testing of stability for switching control law



Force



Position

Review

- In Free Motion, average of error and variance of error are small enough to control.
- Although the precision of force tracking with varying force is a little bad, controllability of the system maintains to enough.
- Although the system was taken 1 [sec] delay for communication, it was stable in any cases.
- In order to use Force control and position control according to contact situation, contact situation is easy to understand.

Conclusion

In this research, I propose the new controller of Tele-Manipulation system with hybrid control. And I examine the performance of this controller by experiment using robot manipulator.
The system was confirmed to maintain stability and operatability under the time delay by experiment.

Future Plan

- Apply the system for communication environment with varying time delay.
- Add the environmental observer for the system to reduce position tracking error.