A New Robust Controller Design Architecture of Teleoperation to Overcome the Compensation Problem

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Abstract: There were many papers on the bilateral teleoperation system. But a few papers dealt with the controller design method in the presence of uncertainties, disturbances and measurement noises. In this paper, we propose a robust controller design framework in teleoperation, which can overcome the compensation problem that will be defined. To prove the effectiveness of the method of proposed design, comparative simulation with the existing four channel design method was performed

Keywords: Robustness, Teleoperation, Compensation Problem

1. Introduction

Teleoperation system has been applied to many areas since when Goertz[1] developed the first teleoperation system. There has been many improvements in the controller design of teleoperation system.

To evaluate the system performance and design the controller, the definition of ideal responses of teleoperation systems was introduced. For force-feedback systems, Handlykken[2] suggested that it could be represented by an infinitely stiff and weightless mechanical connection between the end-effector of the master and the slave. After Raju[3] and Hannaford[4], 2-port network description model of teleoperation system has been widely used and the mathematical definition of ideal transparency was described by Lawrence[5] and Yokokohji[7]. As shown in Fig.1, if operators are to feel as if they are touching the task directly, then operator's force on the master F_h and the master's velocity V_h should have the same relationship with the applied force by slave F_e and the slave velocity V_e, i.e. for the same forces $F_e = F_h$ we want the same motion $V_e = V_h$. This requires that the impedance Z_t transmitted to or felt by the operator, defined by $F_h = Z_t(V_h)$, satisfies the transparency condition

$$Z_t = Z_e. \tag{1}$$

To achieve transparency-optimized performance, Lawrence proposed the architecture of general teleoperation system. Independently, Yokokohji[7] also proposed a similar architecture which additionally includes local force feedback block. Recently, H-Zaad[6] also proposed the same structure and emphasized the role of local force feedback which could enhance the stability and performance. But in these design methods of transparency-optimized controller, they assumed that the system parameters of master and slave are exactly known and does not have any disturbances. With this assumption, they could build the controller without knowing the operator and object dynamics. However, since the exact identification of system parameters can not be possible the system always contains parameter errors and additional noises of the acceleration and force signals which may drive the system to unstable. To cope with these problems, many research groups applied the robust control theory deriving stable teleoperation controller.

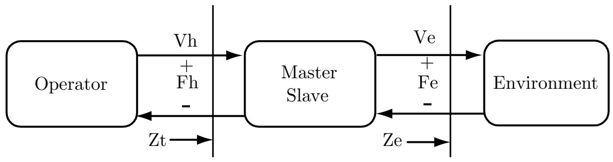

Fig. 1. General 2-ports system model of teleoperation

There were a few papers which concentrated on the controller design in the frame of robust control. In reference [8], H_∞ control theory was applied to the design of the stable controller for the system. In there, the Force-Force type control structure was used. From the control structure, as the author said, the system suffered from a position error buildup between master and slave since neither position nor velocity information of master and slave are transferred to each other.

In reference [11], the H_∞-optimal control theory for the free motion and μ-Synthesis theory for the contact motion were used to derive the controller for the teleoperator which could achieve the stability for a prespecified time delay.

In this control structure, slave always unilaterally follows the velocity of master at free motion. Therefore, if slave makes a contact at the other place where the force sensor is attached to, then the operator does not receive and feel any feedback information of the state of slave from the master controller and could not make the velocity error minimized at all. And the condition of force tracking for the contact motion controller, the master actuator force tracks the environment force, was misused to make the system have an ideal force transparency.

In reference [10], they proposed a general framework for robust teleoperation controller synthesis as shown in Fig. 2 and demonstrated the design examples for free motion and contact motion, respectively. This controller structure is so called "four channel architecture", proposed in [5] and [7], in which the control signals are based on positions as well as on forces. However, this design procedure had the following

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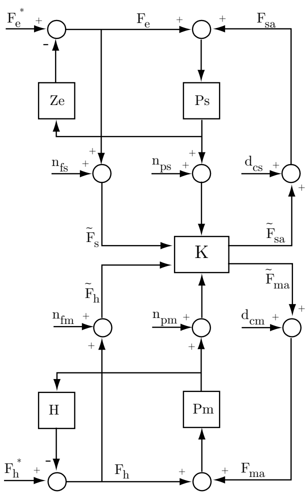
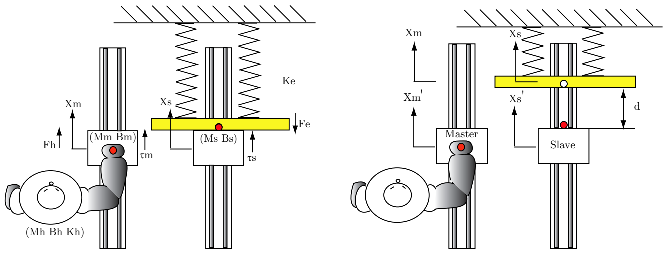


Fig. 2. Robust four channel controller design framework by Yan



(a)Master, slave, operator and wall (b)Free to contact situation

Fig. 3. System Setup

problems.

First, they also misused the condition of ideal force tracking like [11] mentioned above when deriving the controller.

Second, this controller has a critical problem with coordinate transformation which is called compensation problem in this paper. This problem is caused by the application of the robust control to suggested four channel architecture. Four channel architecture without robustness property [5],[7] does not have this problem since the transparency optimized controller satisfies some conditions which will be mentioned later.

The goal of this paper is to propose a new robust controller design framework of teleoperation, which can achieve the ideal transparency condition for contact motion and overcome the compensation problem which is critical if the robust controller is to be applied to real task.

2. Program statement

2.1. Modeling of System

The dynamics of master and slave is given by the following equations.

$$M_m\ddot{x}_m + B_m\dot{x}_m = \tau_m + F_h \qquad (2)$$

$$M_s\ddot{x}_s + B_s\dot{x}_s = \tau_s - F_e \qquad (3)$$

where $M_m, M_s, B_m, B_s, x_m, x_s, \tau_m$ and τ_s are, respectively, the master and slave masses, viscous coefficients, displacements, and actuator forces. And F_h is the force that the operator applies to the master and is measured by force sensor and F_e is the force that the slave applies to the wall.

The dynamics of the wall is modelled as spring and the correspondent equation is

$$F_s = K_e x_s, \qquad (4)$$

where K_e is the stiffness of the wall. When we design the controller for contact motion, we assume that the wall is rigidly connected to the slave and can not depart from the slave.

To represent the dynamics of the operator, we assume that the operator can be modelled with mass, damper and spring like as following equation.

$$M_h\ddot{x}_m + B_h\dot{x}_m + K_h x_m = F_h^* - F_h \qquad (5)$$

where M_h, B_h, K_h and F_h^* are, respectively, mass, viscous coefficient, stiffness of the operator and force generated by the operator's muscles. And we also assume that the operator is firmly connected to the master and never release it during the operation.

2.2. Problem Statement

Let us examine the situation illustrated in Fig.3-(b). If the robust controller structure by Yan[10] is to be applied to this situation, the controller for free motion and contact motion, respectively, should be derived sequentially and the compensation of the distance between the initial position of slave and wall offset is necessary for the contact controller because the contact controller is derived for the situation as shown in Fig.3-(a). This is called as the compensation problem and is a trivial one in transparency optimized four channel architecture but is a critical one in robust four channel architecture by Yan.

To make clear of this problem, we want to compare the controller with the simple position-position type controller. The PD position-position controller is described in Eq.6.

$$\begin{aligned} \tau_m &= K_{dm}(\dot{x}_s - \dot{x}_m) + K_{pm}(x_s - x_m) \\ \tau_s &= K_{ds}(\dot{x}_m - \dot{x}_s) + K_{ps}(x_m - x_s) \end{aligned} \qquad (6)$$

Because this controller is based on the error signals of position and velocity, the compensation of the distance to the wall($X_m = X_m^{'} - d, X_s = X_s^{'} - d$, as shown in Fig.3-(b)) does not make any problem, which is shown in equation Eq.7.

$$\begin{aligned} \tau_m &= K_{dm}((\dot{x}_s^{'} - \dot{d}) - (\dot{x}_m^{'} - \dot{d})) + K_{pm}((x_s^{'} - d) - (x_m^{'} - d)) \\ &= K_{dm}(\dot{x}_s^{'} - \dot{x}_m^{'}) + K_{pm}(x_s^{'} - x_m^{'}) \\ \tau_s &= K_{ds}((\dot{x}_m^{'} - \dot{d}) - (\dot{x}_s{'} - \dot{d})) + K_{ps}((x_m^{'} - d) - (x_s^{'} - d)) \\ &= K_{ds}(\dot{x}_m^{'} - \dot{x}_s^{'}) + K_{ps}(x_m^{'} - x_s^{'}) \end{aligned} \qquad (7)$$

But the robust four channel controller architecture proposed by Yan[10] uses the position signals and force signals of master and slave as an input to the controller and is represented as following equation.

$$\begin{bmatrix} \tau_m \\ \tau_s \end{bmatrix} = \begin{bmatrix} K_{m1} & K_{m2} & K_{m3} & K_{m4} \\ K_{s1} & K_{s2} & K_{s3} & K_{s4} \end{bmatrix} \begin{bmatrix} x_m \\ x_s \\ F_h \\ F_e \end{bmatrix} \qquad (8)$$

The controller gains of above equation are to be determined to satisfy the prespecified performance via robust control algorithm. If the compensation of the distance to the wall is performed, Eq.9 can be acquired.

$$\begin{bmatrix}\tau_m \\ \tau_s\end{bmatrix} = \begin{bmatrix}K_{m1} & K_{m2} & K_{m3} & K_{m4} \\ K_{s1} & K_{s2} & K_{s3} & K_{s4}\end{bmatrix} \begin{bmatrix}x_m^{'} \\ x_s^{'} \\ F_h \\ F_e\end{bmatrix} - \begin{bmatrix}(K_{m1}+K_{m2})d \\ (K_{s1}+K_s))d\end{bmatrix} \tag{9}$$

Without regard to the compensation of the initial distance to the wall, the response of the contact controller have to be constant. To satisfy this condition, the following relations must be satisfied.

$$\begin{bmatrix}(K_{m1}+K_{m2})d \\ (K_{s1}+K_{s2})d\end{bmatrix} = \begin{bmatrix}0 \\ 0\end{bmatrix} \tag{10}$$

In other words, $d = 0$ or $K_{m1} = -K_{m2}, K_{s1} = -K_{s2}$ can be acquired from the above equation. The first condition, $d = 0$, is a trivial condition because Eq.10 always holds regardless of the gains; K_{m1}, K_{m2}, K_{s1} and K_{s2}. And more the second condition, $K_{m1} = -K_{m2},\ K_{s1} = -K_{s2}$ can not be satisfied because the contact controller is numerically derived by robust control algorithm.

Because the robust contact controller include position information, whose values are varying with the initial setup position, in input signals, the above compensation problem always happens. To remedy this problem, we want to propose a new robust controller design architecture.

2.3. Numerical Example

An example is provided to clear the problem mentioned above. The master and slave have the same mechanical parameters as the following.

$$M_m = M_s = 6.825(kg), B_m = B_s = 27.3(Ns/m)$$

and the parameters of operator are

$$M_h = 2.0(kg), B_h = 2.0(Ns/m), K_h = 10(N/m).$$

The stiffness of the wall has the following value.

$$K_e = 1000(N/m) \tag{11}$$

The robust four channel architecture is to be applied to verifying the existence of the compensation problem. The system block diagram is given in Fig. 2. And as mentioned in [10], P_m and P_s are assumed to be the resulting transfer functions after the use of local controllers to stabilize the master and slave. The PD controller is used as a local controller to make the system have desired dynamics. Local controllers, P_m and P_s have the following relations.

$$\begin{aligned} K_{lcm} &= B_{cm}s + K_{cm} \\ K_{lcs} &= B_{cs}s + K_{cs} \\ P_m &= \frac{K_{lcm}}{1 + Master * K_{lcm}} \\ P_s &= \frac{K_{lcs}}{1 + Slave * K_{lcs}} \end{aligned} \tag{12}$$

where K_{lcm} and K_{lcs} are the local controller of master and slave, respectively.

The parameters of the local controller from the desired dynamics of master and slave which can be described by the damping coefficients(ζ_m and ζ_s)and natural frequencies(ω_m and ω_s) can be derived via the following equations.

$$\begin{aligned} \frac{P_m}{1+P_mH} &= \frac{1}{(M_m+M_h)(s^2+2\zeta_m\omega_m s+\omega_m^2)} \\ \frac{P_s}{1+P_sE} &= \frac{1}{M_s s^2+(B_s+B_{cs})s+(K_{cs}+K_e)} \end{aligned} \tag{13}$$

where H and E are the impedance model of human and envirionment, respectively.

The performance index of this design is described as the following.

$$\begin{bmatrix}z_1 \\ z_2 \\ z_3 \\ z_4\end{bmatrix} = \begin{bmatrix}W_1(x_m - x_s) \\ W_2(F_h - F_e) \\ W_3F_{ma} \\ W_4F_{sa}\end{bmatrix} \tag{14}$$

where z_1 and z_2 are performance index for the position tracking error and force tracking error and z_3 and z_4 are for the saturation limits of the master and slave actuators, respectively. And the weighting function used are $W_1 = (s+1000)^2/(s+10)^2,\ W_2 = 0.2(s+30\pi)/(5s+30\pi),\ W3 = W4 = (0.05s+1)/(s+200)$. The weighting function W_1 is determined to make the position error less than 1mm at low frequency and W_2 is to make the force tracking error less than 5N at low frequency and finally $W_3,\ W_4$ is to make the saturation limits of actuator force at 200N.

The one different point from that of Yan[10] is the force tracking performance. They used $z_2 = W_2(F_{ma} - n_fF_e)$, where the signal F_{ma} is defined in Fig.2 as actuator force of master and n_f is a desired force scaling factor because they used the controller to the motion scaling teleoperation. However, because $z_2 = W_2(F_{ma} - n_fF_e)$ is not an ideal force tracking condition, this condition is replace by $z_2 = W_2(F_h - F_e)$, which is an ideal force tracking condition.

The simulation response to the input force, $F_h^* = 10$N step, is shown in Fig.4. As shown in the figure, the controller make the system stable and satisfy the prespecified performance index when $d = 0$.

To make observation of the compensation problem, we set $F_h^* = 0$N and add the value 0.1m to the positions of master and slave intentionally. The result of this simulation is shown in Fig.5. As we mentioned in problem statement, we can see the compensation problem from this result. If this controller does not have this problem, all the signals plotted in Fig.5 must have the value 0. This problem is caused because the contact controller which is derived numerically by robust control algorithm doesn't satisfy Eq.10. From this result, we can conclude that the robust four channel architecture works well only if initially contact condition($d = 0$) holds.

Let us take another task which includes both free and contact motion as shown in Fig.3-(a). To simulate this task, we set $F_h^* = 10$N and $d = 0.1$m and switch the controller from the

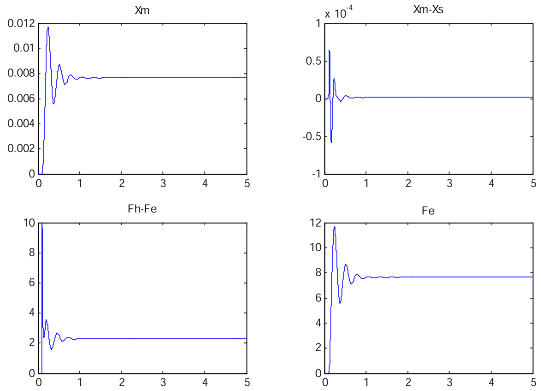


Fig. 4. Simulation results of robust four channel architecture suggested by Yan for the contact motion

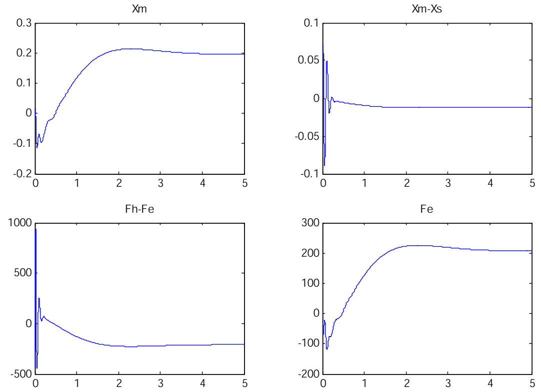


Fig. 5. Simulation results of robust four channel architecture suggested by Yan for the contact motion to show the compensation problem

free motion to the contact motion when the slave initially contacts with the wall. Simulation result is shown in Fig.6. As shown in the figure, the behavior of the master and slave is similar with Fig.5 after initial contact with the wall.

3. Design Methodology

As mentioned above, the compensation problem always happens when the robust controller for the four channel architecture is derived with the approach of Yan. Therefore, in this paper the robust four channel architecture design methodology which can overcome this problem is to be proposed. This methodology is composed of two design stage. At first the design method for the free motion will be introduced and then the design method for the contact motion will be proposed based on the free motion controller and force sensor signals only.

3.1. Design Methodology for free motion

There are two architecture for the free motion. One is unilateral position architecture and the other is bilateral position-position architecture. The unilateral position architecture had been used in the position-force architecture which has the same structure with this because there is not any feedback force from the slave when the slave does not contact with the wall. There are some problems in this architecture. First, as the slave unilaterally have to follow the master in

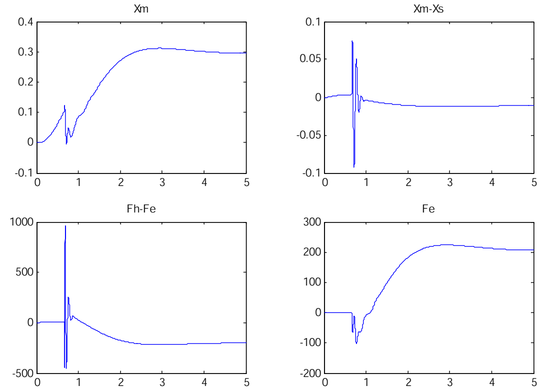


Fig. 6. Simulation results of robust four channel architecture suggested by Yan for the free to contact motion to show the compensation problem

free motion, the desired dynamics of the slave must have much more fast one than that of the master. Second, as mentioned above, if slave makes a contact at the other place where the force sensor is attached to, then the operator does not receive and feel any feedback information of the state of slave from the master controller and can not make the velocity error minimized at all.
From these kinds of drawback of the unilateral position architecture, the bilateral PD position-position design method would be applied for the free motion. This position-position method also had been used to the contact motion but has not been used because the position-position architecture only does not provide the transparency for the contact motion and good position control on the master increases the size of the effective inertia, leading to a sluggish feel in the free motion. However, This position-position architecture works well with the force-force architecture for the contact motion, which result to the conventional four channel architecture. The gain selection of the PD controller should take these properties into account. The free motion structure of the system is shown in Fig.7, where the free motion controller can be described as the following equation.

$$\begin{bmatrix} \tau_m \\ \tau_s \end{bmatrix} = \begin{bmatrix} -C_{m1} & C_{m2} \\ C_{s2} & -C_{s1} \end{bmatrix} \begin{bmatrix} x_m \\ x_s \end{bmatrix}$$

The gains of this position-position controller have to satisfy the following condition to minimize the tracking errors and also satisfy Eq.10.

$$\begin{aligned} C_{m2} &= C_{m1} \\ C_{s2} &= C_{s1} \end{aligned} \tag{15}$$

If the PD controller is applied to this structure, the free motion controller can be represented as the following equation.

$$\begin{aligned} C_{m2} = C_{m1} &= K_{dm}s + K_{pm} \\ C_{s2} = C_{s1} &= K_{ds}s + K_{ps} \end{aligned} \tag{16}$$

The parameters of this controller, K_{dm}, K_{ds}, K_{pm} and K_{ps}, can be founded from the desired dynamics of master and slave which can be parameterized by the desired damping coefficients(ω_m, ω_s) and natural frequencies(ζ_m, ζ_s).

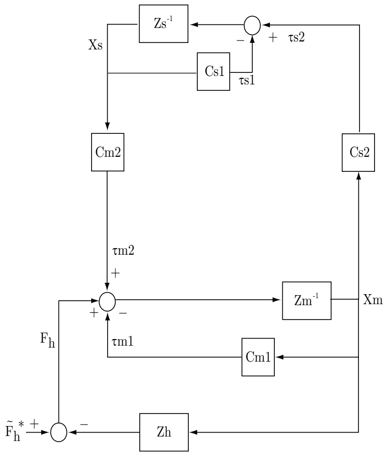


Fig. 7. Controller design framework for the free motion: Bilateral position-position architecture

Because this desired dynamics of master and slave is closely related with the performances for the free motion, the desired parameters are to be carefully chosen to have the position error less than the allowable one.

$$\begin{aligned} \frac{1}{Z_m + Z_h + C_{m1}} &= \frac{1}{(M_m + M_h)(s^2 + 2\zeta_m \omega_m s + \omega_m^2)} \\ \frac{1}{Z_s + C_{s1}} &= \frac{1}{M_s(s^2 + 2\zeta_s \omega_s s + \omega_s^2)} \end{aligned} \tag{17}$$

From Eq.17, the controller parameters can be represented with the other system parameters like as Eq.18.

$$\begin{aligned} K_{dm} &= 2(M_m + M_h)\zeta_m \omega_m - (B_m + B_h) \\ K_{pm} &= (M_m + M_h)(\omega_m^2) - K_h \\ K_{ds} &= 2M_s \zeta_s \omega_s - B_s \\ K_{ps} &= M_s \omega_s^2 \end{aligned} \tag{18}$$

3.2. Design Methodology for contact motion

After designing the free motion controller, we have to add the additional force based controller to pre-designed free motion controller for the contact motion. Since pre-designed free motion controller always satisfies Eq.10, the compensation problem will not happen anymore. And the additional force based controller help the free motion controller to make the system have good performance and stability. This is the basic idea of the robust four channel controller design for the contact motion.

The system architecture for the contact motion is shown in Fig.8. The wall, an additional force based controller block K, uncertainties of the plant, the disturbances of force and velocity are added to the architecture for the free motion, which is shown in Fig.7. And this architecture can be formulated in the framework of μ-Synthesis, which is shown in Fig.9.

The interpretation of the signals, weighting functions and models are

- $\hat{F}_h^*$ is a normalized exogenous force by human's muscle
- $\hat{F}_{nm}$ and $\hat{F}_{ns}$ are a normalized exogenous force disturbance measured at master and slave side, respectively.
- $\hat{V}_{nm}$ and $\hat{V}_{ns}$ are a normalized velocity noise at master and slave side, respectively.
- W_{fh} shapes (magnitude and frequency) the normalized exogenous force signal into the actual exogenous force that we expect to occur. Normally W_{fh} is flat at low frequency and rolls off at high frequency.
- W_{fm} and W_{fs} shape the normalized exogenous force disturbance measured at master and slave into the actual exogenous force disturbance, respectively.
- W_{vm} and W_{vs} represent the frequency domain model of velocity noise of master and slave, respectively. when we set up the hardware system, we usually measure the position with digital encoder and then acquire the velocity by a numerical derivatives. So, the velocity signal is more noisy than the position signal. this is why we assume the velocity noise in proposed framework.
- W_{um} and W_{us} represent the frequency domain model of system uncertainty of master and slave, respectively.

The performance indexes of μ-Synthesis formulation for the contact controller of teleoperation can be described as the following. There can be another ones but the following four performance indexes are enough to derive the robust controller for teleoperation.

- $e_1 = W_P(X_m - X_s)$: W_P weights the difference between the position of master and the position of slave. Often we desire accurate tracking of position at low frequency and require less accurate tracking at higher frequency, in which case W_P is flat at low frequency, rolls off at first or second order, and flattens out at a small, non-zero value at high frequency. From the normalization characteristics of μ-synthesis algorithm, the inverse of this weight should be related to the allowable size of tracking error, in the face of the exogenous force input and disturbances.
- $e_2 = W_F(F_h - F_e)$: W_F weights the difference between the measured force at master and the measured force at slave. W_F is determined by the similar reasoning with W_P because the required frequency response are similar with W_P, in other words, accurate tracking of position at low frequency and less accurate tracking at higher frequency are required.
- $e_3 = W_{Tm}(-\tau_{m1} + \tau_{m2} + u_m)$: W_{Tm} is frequency varying weighting function used to penalize limits on the force of master actuator, in the face of tracking and disturbance rejection objectives. The actuator force is composed of two terms. One is the position based term, i.e. free motion controller, which are represented as τ_{m1} and τ_{m2} and the other is force based term which is represented as u_m in Fig.8. Therefore we have to weight the summation of these two terms to take the actuator saturation into account. The frequency response of W_{Tm} can be determined in consideration of the bandwidth and the peak force of the actuator.
- $e_4 = W_{Ts}(-\tau_{s1} + \tau_{s2} + u_s)$: W_{Ts} is frequency varying weighting function used to penalize limits on the force of slave actuator. W_{Ts} is determined by the same reasoning with W_{Tm}.

4. Design Example

One design example will be presented in this section to verify the design methodology mentioned above. At first, the free motion controller will be designed and simulated. And then

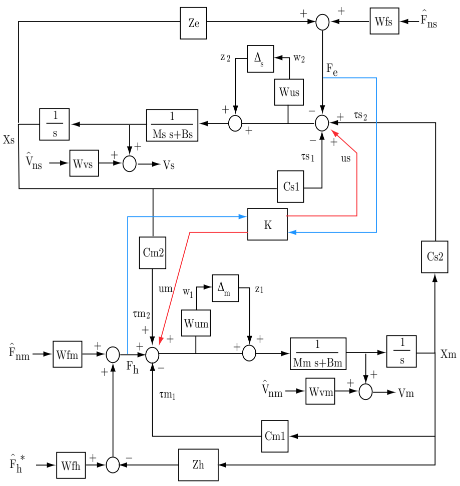


Fig. 8. Controller design framework for the contact motion

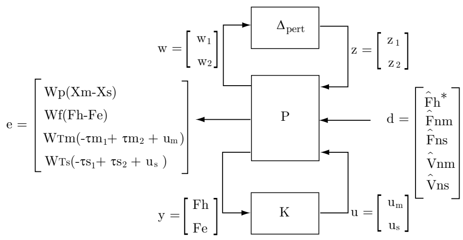


Fig. 9. μ-Synthesis problem formulation for the contact motion

based on this free motion controller, the contact motion controller will be also designed and simulated. To formulate the problem and derive the contact controller in the framework of μ-Synthesis, the "μ-Analysis and Synthesis Toolbox"[12] in MATLAB is used and Simulink is also used to simulate the derived controller. Finally, the simulation will be performed to the situation shown in Fig.3-(b) with the derived controller.

Let us look at the free motion controller. If the desired damping coefficients and the desired natural frequencies is set like as the following values,

$$\zeta_m = \zeta_s = 0.7,\ \omega_m = 5Hz,\ \omega_s = 10Hz \tag{19}$$

The position based controller terms, C_{m1}, C_{m2}, C_{s1} and C_{s2} can be acquired. The simulation result of this derived controller to an input, $F_h^* = 10$N, is shown in Fig.10. As shown in this figure, the positions of master and slave are increasing and are going to go to the final value and the position error has a tendency to decrease.

And next, Let us look at the example of the controller design for the contact motion. With the position based controllers, C_{m1}, C_{m2}, C_{s1} and C_{s2}, which were designed for the free motion, the weighting functions used here are $W_{fh} = 10/(6\pi s+1)$, $W_{fm} = W_{fs} = 0.01(1/20\pi s+1)/(1/100\pi s+1)$, $W_{um} = W_{us} = 0.05(1/20\pi s+1)/(1/200\pi s+1)$, $W_{vm} = W_{vs} = 0.005(1/20\pi s+1)(1/60\pi s+1)$, $W_P = 1000(1/30\pi s+1)(1/6\pi s+1)$, $W_F = 0.5(1/30\pi s+1)(1/6\pi s+1)$.

And the additional force based controller term for contact motion has the following input-output relation and the purpose of μ-Synthesis is to get this relation.

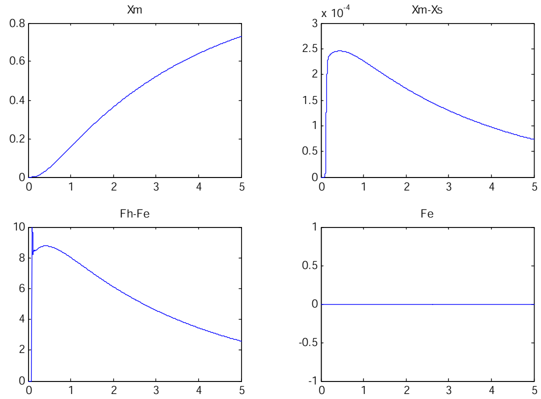


Fig. 10. The simulation results of the free motion to $F_h^* = 10$N

$$\begin{bmatrix} u_m \\ u_s \end{bmatrix} = \begin{bmatrix} K_{m1} & K_{m2} \\ K_{s1} & K_{s2} \end{bmatrix} \begin{bmatrix} F_h \\ F_s \end{bmatrix} \tag{20}$$

The performance index of $e_1 = W_P(X_m - X_s)$ and $e_2 = W_F(F_m - F_e)$ are used to derive K_{m1}, K_{m2}, K_{s1} and K_{s2}. In this example, the actuator saturation is not included to get the controller but this can be also included. The "dkitgui" command in μ-Analysis and Synthesis toolbox, which solves the problem by "D-K iteration" method, are used to derive the controller. This command calculates the peak μ values and the peak μ value of this design example for contact motion is 0.884, which means the additional force base controller achieves robust performance from Eq.**??**, and the order of the controller is 23. This controller can be reduced by the balanced model reduction but is not reduced because we want to see the exact result of this controller.

when we assume there are no uncertainties and noises in this system, the result of $F_h^* = 10$N step is shown in Fig.11. Since the stiffness of the wall is 1000 N/m and the exogenous input force is 10N, if the derived contact controller is a ideal one to make the system satisfy the ideal transparency condition, the position of master and slave at steady state have to be 0.01m in front of the initial position and the force tracking error, $(F_h - F_e)$, have to go zero asymptotically. Fig.11 shows that the position tracking error is below 1mm and the force tracking error is below 2N at steady state. This result satisfies the prespecified performance indexes of the problem formulation.

The existence of this robust controller totally depends on the conditions of W_F and W_P. If the desired performances are set to be more loose than the used one of this design example, there may be the controller which has low orders but bad performance and the possibility of existence of that controller will be larger than the used one of above design example.

Finally, the simulation for the situation shown in Fig.3-(b) are to be performed. The initial setup of this simulation is that the distance to the wall from the initial position of slave is 0.1m, which exact value is not important at all for this simulation and is just used to interpret the result. The

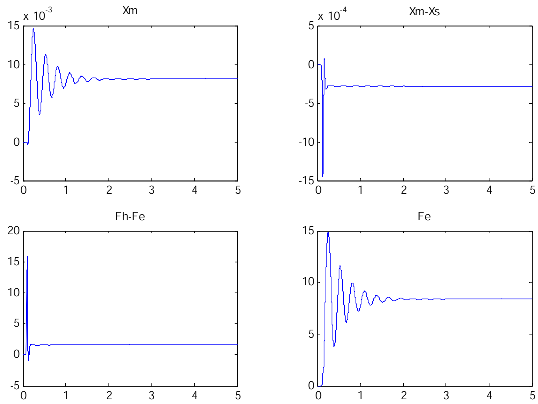


Fig. 11. Simulation results of the proposed robust controller design method for the contact motion: Without noises and uncertainties and $F_h^* = 10$N

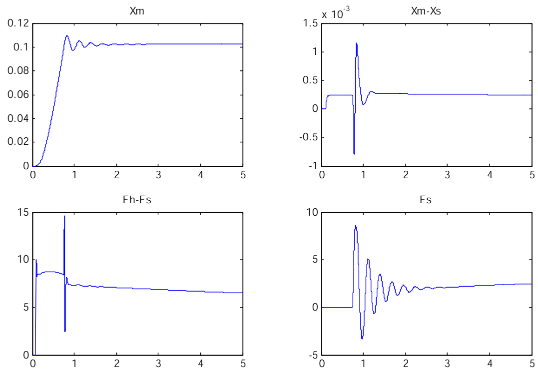


Fig. 12. Simulation results of the proposed robust controller design method for the free to contact motion: Without noises and uncertainties and $F_h^* = 10$N

assumption of this simulation is that the slave is rigidly connected to the wall and cannot depart from the wall after initial contact with the wall, as mention earlier. The simulation result of the system without uncertainties and noises to $F_h^* = 10$N can be shown in Fig.12.

As described in problem statement, the previous robust four channel control architecture which are based on positions and forces always has the compensation problem. But the proposed design method can overcome this problem.

5. Conclusion

A new robust controller design framework to overcome the compensation problem which is defined in this paper has been presented. The proposed method takes both the free motion and contact motion into account when deriving the controller. Therefore, this proposed method can be applied to the realistic situation which includes the transition motion like as free to contact motion. The design example compares the performance with the other robust controller design method and shows the effectiveness of this method.

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