UPPER LIMB MOTION ASSIST ROBOT

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Abstract - An upper limb motion assist robot to elderly and disabled people is proposed in this paper. The robot can be mounted on a wheelchair to actuate an elderly person’s upper limb three dimensionally by his will. A wrist of an arm is suspended, and actuated by a wire driven control system. A vibration reduction system is also developed to decrease the vibration occurred in the wire driven system. The wire driven control system is advantageous to design a compact, light weight, and low cost mechanism. In this paper, the concept of the robot, the mechanical structure of an experimental setup, mechanical characteristics, control system, experimental results are described.

1. INTRODUCTION

A rapid growth of elderly population causes the shortage of care workers. Therefore, it is necessary to develop assist robots capable of supporting such an aged society [1]. Many assist robots in which an elderly person can support himself have been fabricated [1-10].

There is a tendency that an elderly person can not lift up his arm since his muscular strength is declining though his hands still operate normally. When an elderly person can lift up his arm by his own will, then an elderly person can improve his quality of life. Tateno et al. proposed the upper limb motion assist robot by which elderly and disable people can move their arm by their own will [2]. The vibration occurred in the suspended structure was one of the problems. Lum et al. used an industrial robot [5]. Homma also proposed an upper limb assist system [3,4]. The robot is using strings to actuate an elderly person’s arm because of its safe property. However, the proposed drive system is a kind of a parallel mechanism in which complicated calculation is required.

The robot system proposed in this paper is using a wire driven control system by which an elderly person’s wrist is actuated three dimensionally in the orthogonal coordinates. The wire driven control system [6] is advantageous to design a compact, light weight, and low cost mechanism, which makes it possible to mount the robot on a wheelchair. In addition, a vibration reduction system is also developed in order to decrease the vibration occurred in the wire driven system. In this paper, the concept of the robot, the mechanical structure of an experimental setup, the mechanical characteristics, the control system, and the experimental results are described.

2. PROPOSED UPPER LIMB MOTION ASSIST ROBOT

Fig.1 shows the concept of the upper limb motion assist robot proposed in this paper. An elderly person who can use his hand but can not lift up his arm by his own muscular strength is supposed to be an user of the upper limb motion assist robot.

The robot has a frame structure to stand vertical to the ground, like a window frame. Two wire driven systems in the X and Z directions are mounted on the frame structure. One wrist of an elderly person is suspended by wires, and actuated in the X and Z directions. In addition, the frame structure is also actuated in the Y direction by using Y drive system. Therefore, an elderly person can move his arm in the three orthogonal coordinates. The field of vision is maintained since the wire used in the robot system is very thin. The wire driven system is advantageous to design a light weight, compact, and low cost mechanism. The robot system can be mounted on a wheelchair as shown in Fig.1. The weight increase of a wheel chair by mounting the robot will be small.

As an interface between a human and the robot, the following instruction systems can be considered; a voice instruction system, an eye movement instruction system, a neck movement instruction system, and a touch panel instruction system and so on.

Fig.2 shows the comparison between a cantilever type actuator and a wire driven type actuator. When using a wire driven type actuator, a lower power and smaller mechanism can be designed.

3. MECHANICAL CONSTRUCTION OF EXPERIMENTAL SETUP

The experimental setup of the X and Z drive systems shown in Fig.3 was fabricated to confirm the concept of the upper limb motion assist robot. Both of the X and Z drive systems were mounted on a one plate. A dummy mass and a plastic arm were used instead of an actual hand and arm. The wire suspended the dummy mass attached to the tip of the arm. Both of the drive systems were using a potentiometer and a DC motor as a sensor and an actuator respectively. The DC motor rotated pulleys, and then the wires were actuated.

In the vertical (Z) drive system, a DC motor drove the wires, and then the wires actuated the dummy mass. The vertical (Z) drive system was mounted on two sliders of the horizontal (X) drive system, and then was driven in the horizontal direction. The two sliders were driven simultaneously by four pulleys, wires, and a DC motor. The position of the two sliders was detected by a potentiometer. The dummy mass position differs from the position of the sliders because of vibration. Therefore, a laser sensor was used to detect the dummy mass position.

4. MECHANICAL CHARACTURISTICS OF HORIZONTAL DRIVE SYSTEM

The positioning control was carried out in the horizontal (X) and vertical (Z) drive systems using a personal computer with an A/D and D/A board. Classical proportional (P) control was used as a control theory. Large amplitude vibration was not occurred in the vertical (Z) drive system. However, large amplitude vibration occurred in the horizontal direction. The frequency of the dummy mass vibration was about 2.56 Hz. The frequency of the dummy mass vibration was changed depending on the vertical position of the dummy mass.

The analysis of the dummy mass vibration was carried out focusing on the frequency change of the dummy mass vibration. Fig.4 shows the dynamical model of the suspended dummy mass. Here,

x : Dummy mass displacement in the X direction
F_1 and F_2 : Tensions
f_{01} and f_{02} : Initial tensions
α and β : Angles
r_1 and r_2 : Wire lengths in the upper and lower sides during when the dummy mass is vibrated
L : Initial total wire length
L_1 and L_2 : Initial wire lengths in the upper and lower sides

The dynamical equation in the X direction becomes as

$$M\frac{d^2x}{dt^2} = -(F_1 + f_{01})\sin\alpha - (F_2 + f_{02})\sin\beta \qquad (1)$$

Also the next relations can be obtained from Fig.4,

$$\begin{aligned} L_1 &= r_1\cos\alpha \\ L_2 &= r_2\cos\beta \\ x &= r_1\sin\alpha = r_2\sin\beta \end{aligned} \qquad (2)$$

Using the equation (2), the dynamical equation becomes as

$$M\frac{d^2x}{dt^2} = -\left(\frac{F_1 + f_{01}}{L_1}\right)x\cos\alpha - \left(\frac{F_2 + f_{02}}{L_2}\right)x\cos\beta \qquad (3)$$

Assuming that the dummy mass is in the center position in the Z direction, the displacement of the dummy mass is small enough, and the angles of α and β are entirely less than one,

$$\cos\alpha \approx 1 \text{ and } \cos\beta \approx 1 \qquad (4)$$

Then, the dynamical equation becomes as,

$$M\frac{d^2x}{dt^2}=-\left(\frac{F_1+f_{01}}{L_1}+\frac{F_2+f_{02}}{L_2}\right)x \quad (5)$$

The spring stiffness is thus as follows.

$$K_{sp}=\frac{F_1+f_{01}}{L_1}+\frac{F_2+f_{02}}{L_2} \qquad (6)$$

Here, the next relations can be obtained when the displacement x is small enough,

$$L=L_1+L_2 \qquad (7)$$

$$F_1+f_{01}=F_2+f_{02}+M\cdot g \qquad (8)$$

Using the equations of (7) and (8), the relation between the spring stiffness and the vertical position of the dummy mass becomes as,

$$K_{sp}=\frac{L(F_1+f_{01})-L_1Mg}{L_1(L-L_1)} \qquad (9)$$

Finally, the relation between the mechanical resonance frequency and the dummy mass vertical position becomes as,

$$f=\frac{1}{2\pi}\sqrt{\frac{K_{sp}}{M}} =\frac{1}{2\pi}\sqrt{\frac{1}{M}\left(\frac{L(F_1+f_{01})-L_1Mg}{L_1(L-L_1)}\right)} \qquad (10)$$

5. SIMULATION OF MECHANICAL RESONANCE FREQUENCY

The relations of the mechanical resonance frequency and the vertical position of the dummy mass are simulated using the above mentioned equations. At first, the spring stiffness K_{sp} is obtained by using the experimental results of the mechanical resonance frequency f. Next, the tension F_1 is obtained by using the equation (9). Then, the mechanical resonance frequencies at different vertical position are calculated using the equation (10).

Fig.5 shows the relation between the resonance frequency and the dummy mass position. In the theoretical results, the gravitational effect is considered, and the conditions of $f_{01}=Mg$ and $f_{02}=0$ are utilized. The theoretical results show the good correlation with the experimental results. When the dummy mass approaches the center of the vertical stroke, the resonance frequency tends to be low. The vibration is worst at the center of the vertical stroke.

6. MATHEMATICAL MODEL OF HORIZONTAL DRIVE SYSTEM

The linear displacement of the slider is almost in proportional to the rotational displacement of the DC motor. However, the displacement of the dummy mass is not in proportion to the displacement of the DC motor due to the vibration of the wire driven mechanism. Hence, the controlled object can be modeled as two mass dynamical systems. The first mass system consists of two sliders and a rotational system including the DC motor etc. The second mass system consists of a linear movement system of the dummy mass and the arm etc. Therefore, the horizontal drive system is modeled as follows.

$$J\frac{d^2\theta}{dt^2}+\left(K_{cr}+\frac{K_tK_e}{R_a}\right)\frac{d\theta}{dt}+K_{gh}^2K_{sp}K_{gp}^2\theta+K_{gp}K_{gh}K_{sp}x_s=\frac{K_tK_{pa}}{R_a}v$$

$$M\frac{d^2x_s}{dt^2}+K_d\frac{dx_s}{dt}+K_{sp}x_s+K_{gh}K_{gp}K_{sp}\theta=0$$

$$y=K_dx_s \tag{11}$$

where,

M : Mass
J : Moment of inertia
K_{cr} : Damping factor of the rotational system
K_{gp} : Translation coefficient of the pulley
K_t : Torque constant of the DC motor
R_a : Resistance of the DC motor
K_{pa} : Power amplifier gain
K_e : Back-electromotive force constant of the DC motor
K_{sp} : Spring stiffness
K_{cl} : Damping factor of the linear system
K_{gh} : Gear ratio
K_d : Transducer coefficient
v : Input voltage of the DC motor

7. VIBRATION REDUCTION USING CLASSICAL CONTROL

The vibration reduction using a classical control is discussed in this section. A personal computer with a A/D and D/A board is used as a controller as shown in Fig.6. Where, the experimental setup using the moving sensor was used. The laser sensor is attached to the slider of the horizontal drive system. The moving sensor control loop is our proposed scheme to reduce the dummy mass vibration. The laser sensor can detect the displacement between the dummy mass and the slider of the horizontal drive system. Fig.7 shows the block diagram of the control system where K_{p1} is the gain on the potentiometer loop, and K_{p2} is the gain on the laser sensor loop. The laser sensor loop does not react when the value of K_{p2} is zero, but vibration reduction control acts proportional to the value of K_{p2}. Figs.8 and 9 show the experimental results with and without the vibration reduction control. It is clear that the laser sensor loop is effective to reduce the vibration.

8. VIBRATION REDUCTION USING OBSERVER BASED OPTIMAL CONTROL

The vibration reduction using an observer based optimal control is carried out in this section. The H_2 control [11] is utilized as an observer based optimal control. The state equation of the controlled system becomes as follows.

$$\begin{aligned} \frac{dx}{dt} &= Ax + B_1 w + B_2 u \\ z &= C_1 x + D_{12} u \qquad (12) \\ y &= C_2 x + D_{21} w \end{aligned}$$

Where, x is the state vector, u is the control input vector, w is the disturbance, z is the output vector for evaluation, t is the time, y is the measured output vector, and C_1, B_1 are the weighting factors. The cost function to be minimized is as follows.

$$J = \int_t^\infty \left\{ u^T u + x^T C_1^T C_1 x \right\} dt \qquad (13)$$

The controller with an observer is as follows.

$$\begin{aligned} \frac{d\hat{x}}{dt} &= A\hat{x} + B_2 \hat{u} + Y C_2^T \left(y - C_2 \hat{x} \right) \\ \hat{u} &= -B_2^T X \hat{x} \end{aligned}$$

(14)

Where, $\hat{u}$ is the control input using the estimated state variables, X and Y are the positive solutions of the following two Riccati equations.

$$\begin{aligned} & X B_2 B_2^T X - A^T X - XA - C_1^T C_1 = 0 \\ & Y C_2^T C_2 Y - Y A^T - AY - B_1 B_1^T = 0 \end{aligned}$$

(15)

The controlled system of the suspended hand can be modeled as follows.

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{K_{sp}}{M} & -\frac{K_{cl}}{M} & \frac{K_{gh} K_{gp} K_{sp}}{M} & 0 \\ 0 & 0 & 0 & 1 \\ \frac{K_{gh} K_{gp} K_{sp}}{J} & 0 & -\frac{K_{gh}^2 K_{gp}^2 K_{sp}}{J} & -\frac{1}{J}\left(\frac{K_t K_e}{R_a} + K_{cr} \right) \end{bmatrix}$$

$$B_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ \frac{b_1 K_t K_{pa}}{J R_a} & 0 & 0 & 0 & 0 \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K_t K_{pa}}{J R_a} \end{bmatrix}$$

$$C_1 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -c_{1a} & 0 & c_{1a}K_{gh}K_{gp} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & c_{1b}K_{gh}K_{gp} & 0 \end{bmatrix}, \qquad D_{12} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$C_2 = \begin{bmatrix} -K_{s1} & 0 & K_{s1}K_{gh}K_{gp} & 0 \\ 0 & 0 & K_{s2}K_{gh}K_{gp} & 0 \end{bmatrix}, \qquad D_{21} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (16)$$

Where, the controller and observer gains are changed by using the values of b_1, c_{1a}, c_{1b}. Fig.10 shows the block diagram of H_2 control system. Fig.11 shows the experimental results using H_2 control. It is clear that the laser sensor loop is effective to reduce the vibration. Compared with the classical control results in Fig.9, the H_2 control results in Fig.11 are superior.

9. CONCLUSIONS

An assist robot for an upper limb motion to elderly or disabled people was proposed in this paper. The proposed robot can be attached to a wheelchair, and can actuate a wrist of an upper limb in three orthogonal directions by a wire driven control system. The wire driven control system is advantageous to design a compact, light weight, and low cost mechanism. In addition, a vibration reduction system was also developed in order to decrease the vibration occurred in the wire driven system. In this paper, the concept of the robot, the mechanical structure of an experimental setup, mechanical characteristics, control system, and the experimental results were described.

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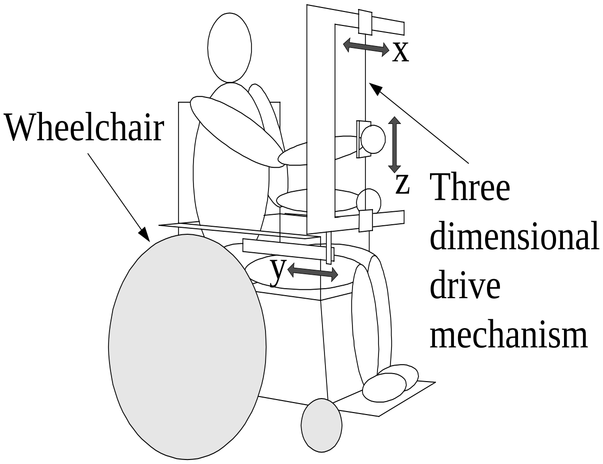
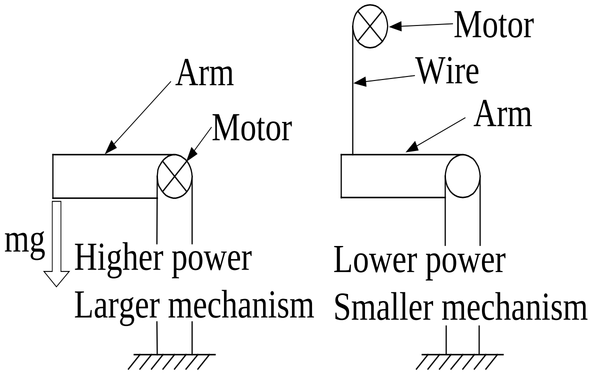


Fig.1 Concept of upper limb motion assist robot



(a) Cantilever type (b) Wire driven type

Fig.2 Comparison between cantilever type and wire driven type

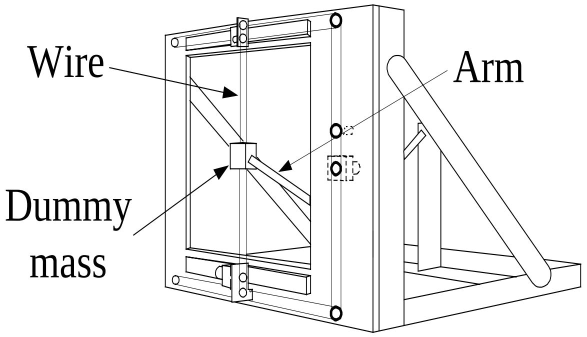


Fig.3 Experimental setup

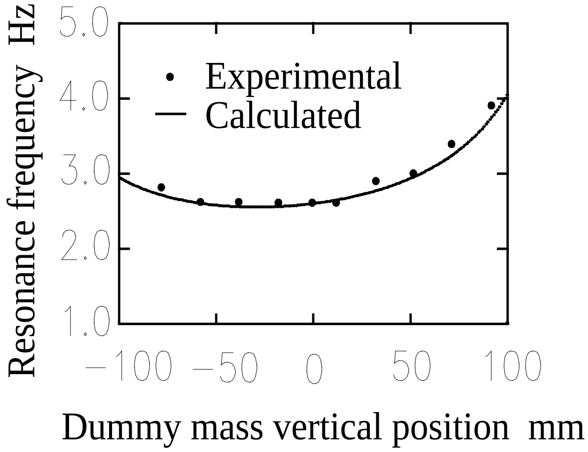


Fig.5 Relation between resonance frequency and dummy mass position

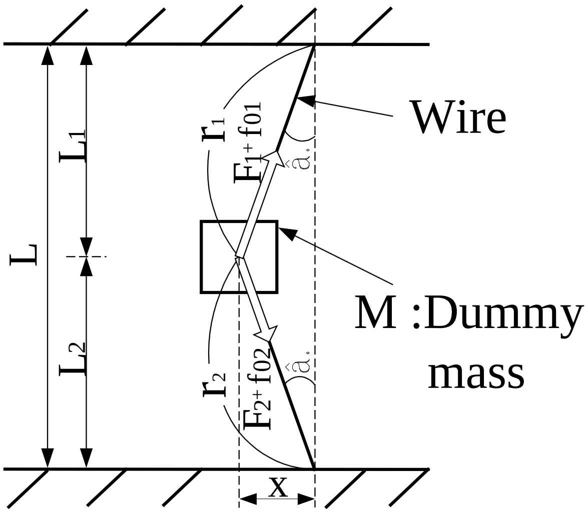


Fig.4 Dynamical model of suspended dummy mass during vibration

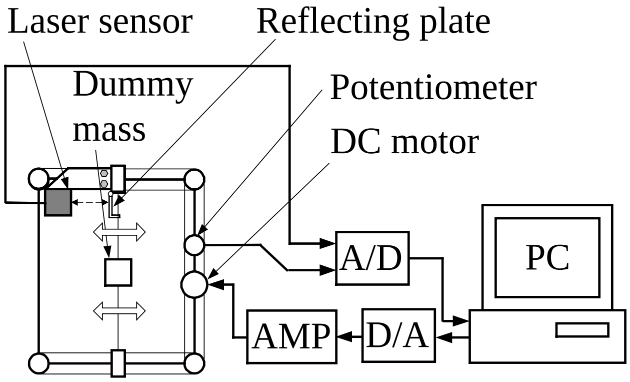


Fig.6 Configuration of control system

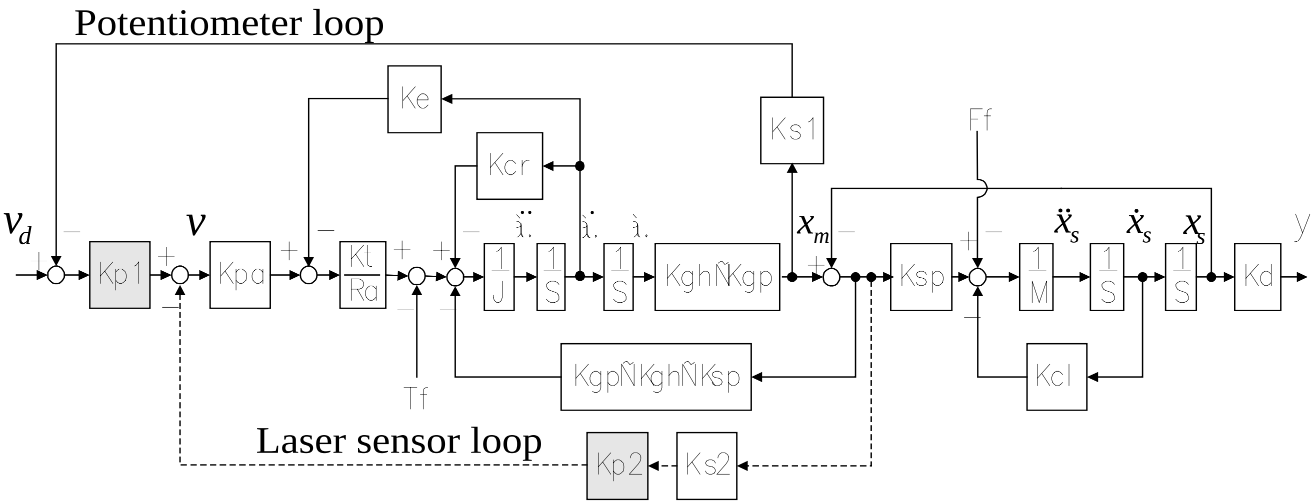


Fig.7 Block diagram of control system

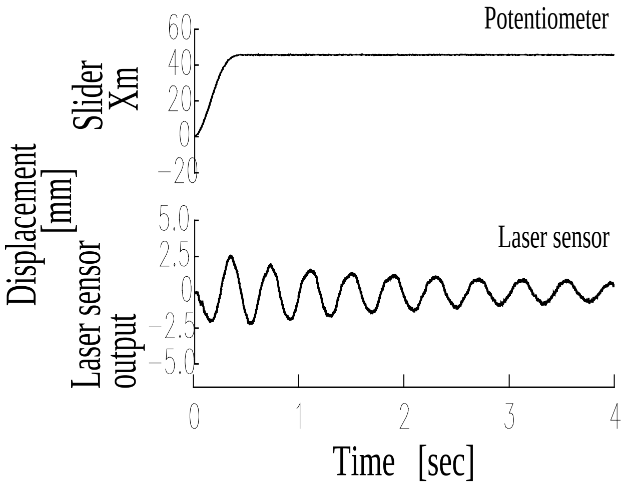


Fig.8 Positioning results without vibration reduction control (Classical control)

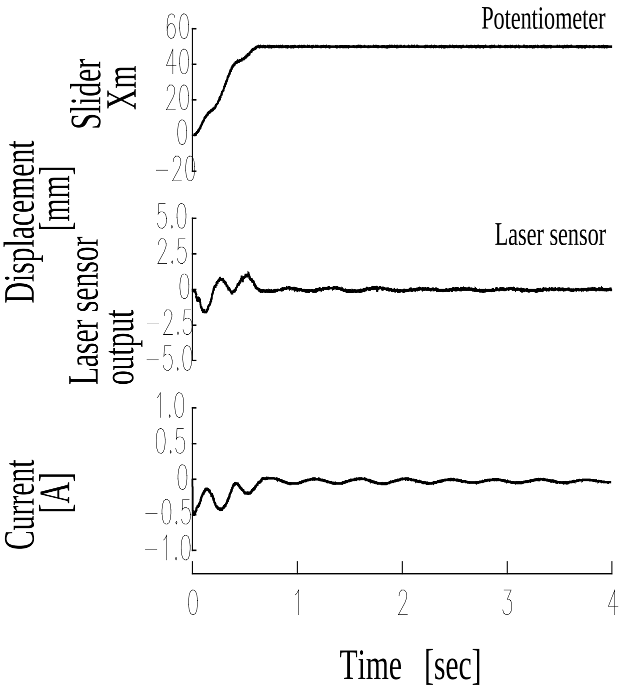


Fig.9 Positioning results with vibration reduction control (Classical control)

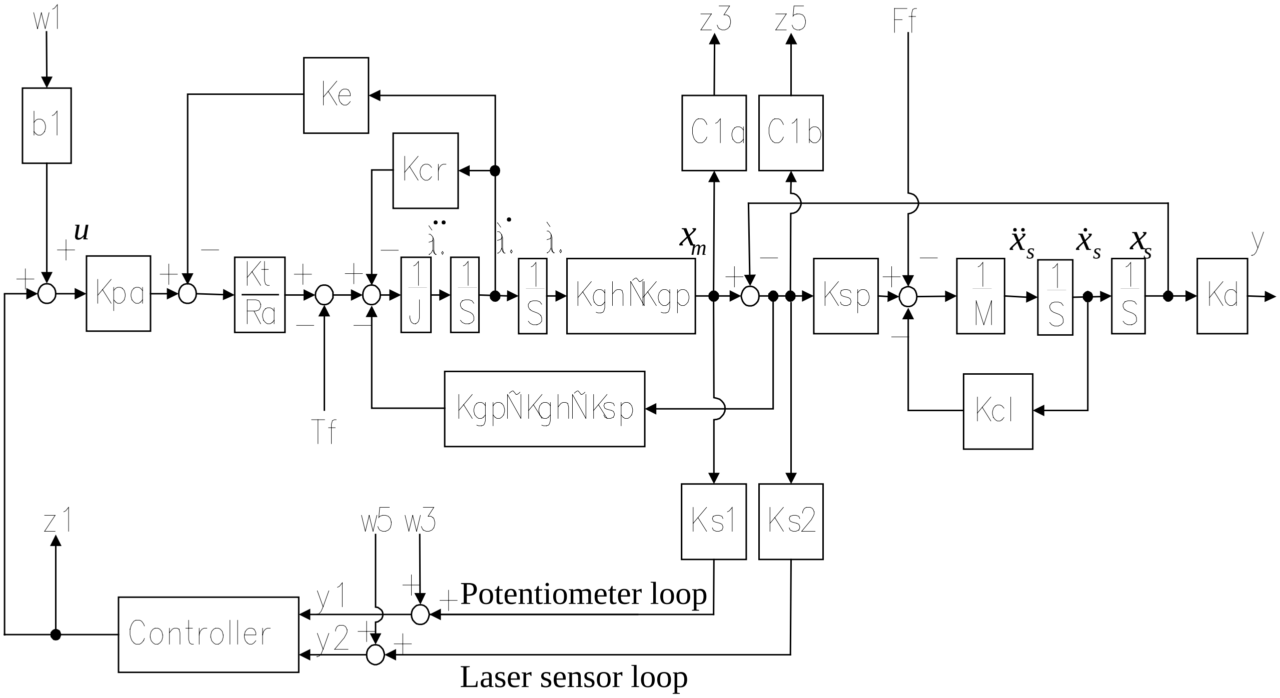


Fig.10 Block diagram of H2 control system

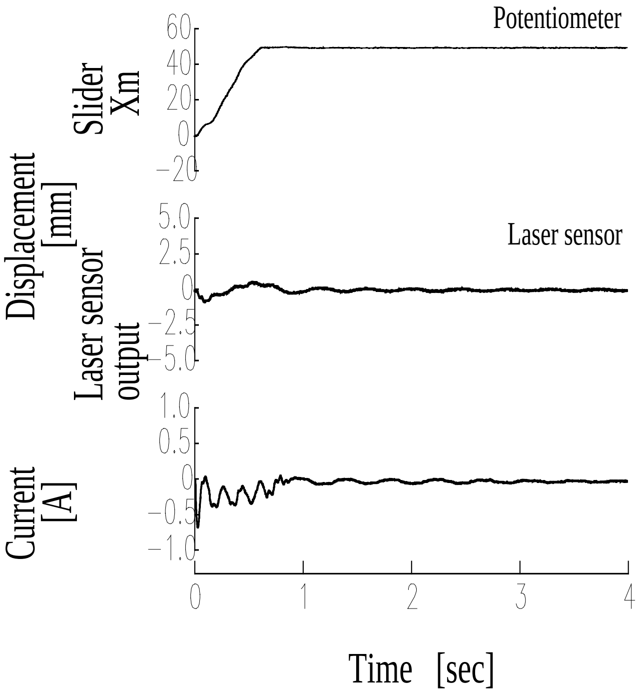


Fig.11 Positioning results with vibration reduction control (H2 control)