



รายงานวิจัยฉบับสมบูรณ์

โครงการ High Sensation of Haptic Feedback in
Robot-Assisted Device based on Acceleration Control with
Compensation of Mechanical Resonance

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สัญญาเลขที่ MRG56-0572

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สนับสนุนโดยสำนักงานกองทุนสนับสนุนการวิจัย

(ความเห็นในรายงานนี้เป็นของผู้วิจัย
สกว.ไม่จำเป็นต้องเห็นด้วยเสมอไป)

รูปแบบ Abstract (บทคัดย่อ)

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**Project Title : High Sensation of Haptic Feedback in Robot-Assisted Device based on
(ชื่อโครงการ) Acceleration Control with Compensation of Mechanical Resonance**

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(ระยะเวลาโครงการ)

This research proposes a specially designed acceleration sensor based load side disturbance observer (ALDOB) with Kalman filtering technique that can be used to estimate the external force on the load side for multi mass system. The proposed observer employs an acceleration sensor and optical encoder to perform contact force measurement. Since acceleration sensors can be implemented in a small area on the end-effector, it is considered to be suitable for the real applications. By using the proposed observer, it is not necessary to identify the nominal spring coefficient.

In the sensorless force control loop, the proposed ALDOB observer can be utilized with resonance ratio control to suppress high-frequency vibrations of spring. Since the optimal parameters are designed by using coefficient diagram method (CDM), the resonance ratio control can ensure good robustness of the force control. The parameters of resonance ratio control for two mass system and three mass system, which are representative of many physical systems are also analyzed by using the proposed method. Moreover, this proposed approach could also be applied for other multi mass system. Our experimental results of the controller's performance including its vibration were in good accord with theory and simulations.

Keywords : (คำหลัก) External force estimation, Kalman filter, Multi mass system, Vibration

รูปแบบ Abstract (บทคัดย่อ)

Project Code : MRG56-0572**(รหัสโครงการ)****Project Title : แรงแผ่นสปริงกลับในหุ่นยนต์ช่วยเลือกการทำงาน โดยการควบคุมความเร่งพร้อม (ชื่อโครงการ) กับการชดเชยการรบกวนของกลไก****Investigator : อ. ดร. เชาวลิต มิตรสันติสุข มหาวิทยาลัยเกษตรศาสตร์ (ชื่อนักวิจัย)****E-mail Address : fengcrm@ku.ac.th, chowarit.ku@gmail.com****Project Period : 2 ปี****(ระยะเวลาโครงการ)**

งานวิจัยฉบับนี้นำเสนอ การออกแบบตัวสังเกตการณ์สัญญาณรบกวนโดยใช้เซนเซอร์วัดความเร่ง และตัวกรองสัญญาณคาบคัลที่สามารถใช้ในการประมาณค่าแรงแผ่นสปริงภายนอกที่ด้านฝั่งของภาระโหลดสำหรับระบบหลายมวล ตัวสังเกตการณ์สัญญาณรบกวนที่นำเสนอประยุกต์ใช้เซนเซอร์วัดความเร่ง และ เซนเซอร์วัดตำแหน่งด้วยวิธีการแสงในการวัดค่าแรงแผ่นสปริง เนื่องจากเซนเซอร์วัดความเร่งสามารถติดตั้งไว้ในพื้นที่ขนาดเล็กที่ด้านปลายแขนของหุ่นยนต์ ทำให้วิธีการดังกล่าวนำไปใช้กับการใช้งานจริงได้อย่างเหมาะสม โดยการใช้ตัวสังเกตการณ์ที่นำเสนอไม่จำเป็นต้องประมาณหาค่าสัมประสิทธิ์ของระบบออกมาก่อน

ในระบบการควบคุมแรงโดยไม่จำเป็นต้องใช้เซนเซอร์วัดแรง ตัวสังเกตการณ์สัญญาณรบกวนสามารถนำมาใช้ร่วมกับการควบคุมอัตราส่วนการสั่นพ้อง เพื่อที่จะลดการสั่นจากความถี่สูงของสปริง เนื่องจากค่าตัวแปรของระบบควบคุมถูกออกแบบให้เหมาะสมโดยการใช้วิธีการแผนผังค่าสัมประสิทธิ์ การควบคุมอัตราส่วนการสั่นพ้องสามารถทำให้มั่นใจได้ว่าระบบควบคุมแรงแผ่นสปริงมีสภาพทนทานที่ดี ค่าตัวแปรของการควบคุมอัตราส่วนการสั่นพ้องทั้งในระบบสองมวล และสามมวล ซึ่งแสดงในระบบกายภาพทั่วไปได้ถูกทำการวิเคราะห์โดยใช้วิธีที่ได้แนะนำดังกล่าวนี้นอกจากนี้วิธีการที่ได้แนะนำยังสามารถนำไปประยุกต์ใช้กับระบบหลายมวลได้อีกด้วย ผลการทดลองประสิทธิภาพของระบบควบคุมในแง่ของการลดการสั่นสะเทือนนั้น มีผลลัพธ์ที่ดีออกมาสอดคล้องกับทฤษฎีและการจำลองด้วยสมการทางคณิตศาสตร์

Keywords : (คำหลัก) การประมาณค่าหาแรงแผ่นสปริงภายนอก, ตัวกรองสัญญาณคาบคัล , ระบบหลายมวล, การสั่น

1 Introduction:

Robotic systems are being built to replace humans in the assistance of performing those repetitive and dangerous tasks which humans are unable to do. For example, industrial robot has been built to perform a task such as pick and place, welding, assembly, painting and product inspection. Robots can probably perform better than a human, because the robot can move more uniformly and more consistently. In the future development of robots, these robots are required to have an ability to accommodate the interaction potential with human operator.

Design of force controls to operate task while contacting with an unknown environments has been described in many papers. Several proposed techniques have paid attention to develop force control system and implemented force sensors to detect the external force. One problem of the using force sensor devices is that they are designed to contact the environment by using strain gauge at the end-effector. As a result, the vibration noise can occur significantly from the soft structure of the strain gauge. To improve the control performance, the observer technique is proposed to estimate the external force without force sensor. Many researches have involved this technique in order to reduce the complicity of the overall control system and increase their stability. Instead of relying on the detection of forces using force sensors, a disturbance observer is capable of estimating disturbance force information. It has been confirmed that efficiency of force estimation and robustness against disturbance can be improved at the same time by using disturbance observer as the feed forward compensation loop. The most important advantage of disturbance observer is that the force bandwidth can be enlarging much higher than the conventional force control with force sensor devices. Unfortunately the disturbance observer posed some challenges that remained unsolved. If such disturbance observer is to be used in a two-mass system with mechanical resonance, the instability and vibration effects can occur and degrade the overall performance. Usually, geared device is applied to increase the torque and reduces the speed of the robot's actuators. It can change the speed direction and torque conversions from the motor to another device. By using geared devices, the motor with gear system is considered as two mass systems. As a result, vibration effect from disturbance observer is occurred due to the mechanical resonance.

To address these problems, a load disturbance observer (LDOB) has been proposed to estimate load side external force by extracting vibration effects from the two-mass system. The structure of the observer is composed of the nominal spring coefficient, the nominal load mass and the encoder, which is attached at the load side. However, its main drawback is that the exact parameters of the spring coefficient are very difficult to obtain.

To get rid of possible parameter mismatch of spring coefficient, a multi encoder based disturbance observer (MEDOB) also provides solutions to estimate the external force at the load side. Since the position of the load side and disturbance force at the motor side can be obtained, parameters identification of spring coefficient is not required. However, its main drawback is that the encoder cannot be easily implemented at the load side due to the space/size limitation.

In this research, a new combined disturbance observer with Kalman filtering technique, named acceleration sensor based load side disturbance observer (ALDOB), has been proposed by using acceleration sensor at the load side and encoder at the motor side. Instead of using encoder to measure position response at the load side, an acceleration sensor is used to measure acceleration information from the end-effectors of the robot. Since acceleration sensors can be implemented in a small area on the load side, it is considered to be suitable for the real applications.

The compensation for vibration effect on the controller accuracy creates further design issues. Yuki et al. have developed a resonance ratio control that can be applied with a disturbance observer to compensate vibration effects in the position control. This idea is used later by Katsura et. al to design sensorless force controller. In this paper, the proposed ALDOB observer can be utilized with resonance ratio control to suppress high-frequency vibrations of spring. Since the optimal parameters are designed by using coefficient diagram method (CDM), the resonance ratio control can ensure good robustness of the force control. The parameters of resonance ratio control for two mass systems and three mass systems, which are representative of many physical systems, are also analyzed. Moreover, this proposed approach could also be applied for other multi mass system. From the simulation and experimental results, it is observed that the oscillations in the contact force response were small. The spring vibrations were significantly reduced in the contact force response.

2 Modeling of Flexible Robot System:

The systems of interest are the linear flexible structures that can be modeled using the two masses connected by a spring as shown in Fig. 1. Since the actuator is connected to the load side with a transmission mechanism, its elasticity causes resonance in the system. A block diagram of the linear motor with two-mass system that controls under the ideal current source is shown in Fig. 2. The equation of motion for such systems is given by:

$$\ddot{X}_M = -\frac{K_S}{M}X_S + \frac{K_T}{M}I_M, \quad (1)$$

$$\ddot{X}_L = \frac{K_S}{L}X_S - \frac{1}{L}F_L, \quad (2)$$

$$\dot{X}_S = \dot{X}_M - \dot{X}_L \quad (3)$$

where subscripts M and L denote the motor side and load side, respectively. K_S is the spring coefficient. F_S and F_L are the spring force and the external force on the load side. K_T is the force coefficient, I_M is the current, X_S is the torsional position from the position of the motor X_M and the position of the load X_L , M and L denote the equivalent mass of the linear motor and load mass,

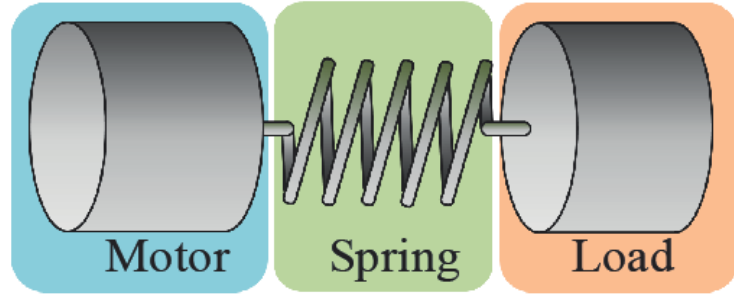


Fig. 1. Modeling of two mass system.

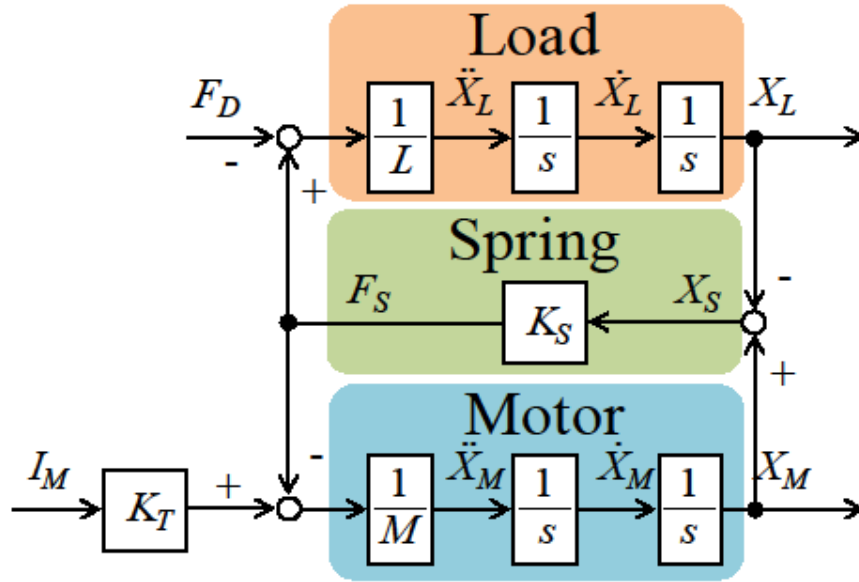


Fig. 2. The block diagram of two mass system.

respectively. Naturally, this flexible transmission can negatively affects the overall performance in terms of increased vibrations.

From Fig. 2, the transfer function from current reference I_M to the velocity of motor side $\dot{X}_M$ and the transfer function from current reference I_M to the velocity of load side $\dot{X}_L$ can be calculated as follows,

$$\frac{\dot{X}_M}{I_M} = \frac{\frac{K_T}{M}(s^2 + \frac{K_S}{L})}{s^3 + (\frac{K_S}{L} + \frac{K_S}{M})s}, \quad (4)$$

$$\frac{\dot{X}_L}{I_M} = \frac{\frac{K_T K_S}{ML}}{s^3 + (\frac{K_S}{L} + \frac{K_S}{M})s}. \quad (5)$$

Then, the anti-resonance ω_{AR} and resonance frequencies ω_R can be described as follows,

$$\omega_R = \sqrt{\frac{K_S}{L} + \frac{K_S}{M}}, \quad (6)$$

$$\omega_{AR} = \sqrt{\frac{K_S}{L}}. \quad (7)$$

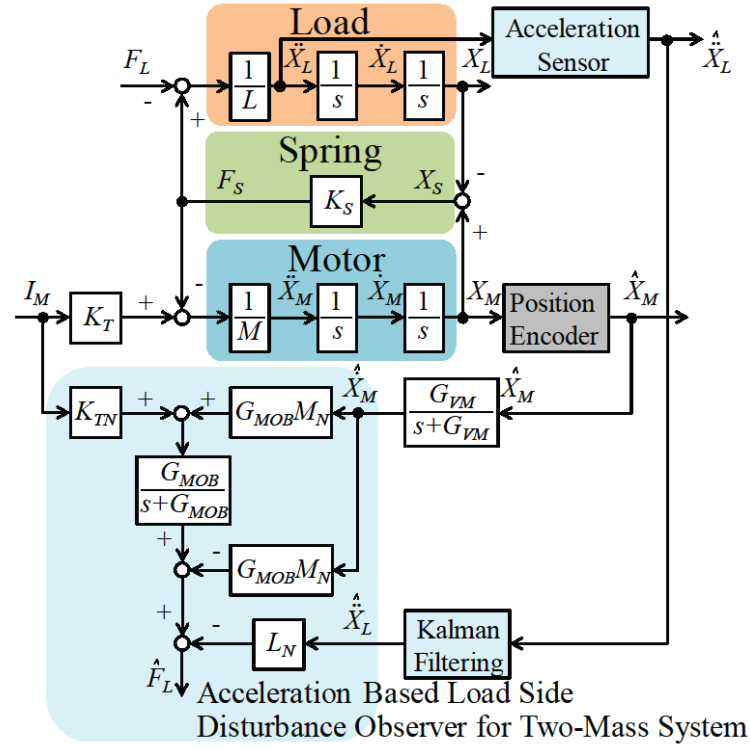


Fig. 3. Schematic diagram of Acceleration Sensor based Load Side Disturbance Observer for two mass system

3 Observer Based External Force Estimation:

One problem of the using force sensor devices is that they are designed to contact the environment by using strain gauge at the end-effector. As a result, the vibration noise can occur significantly from the soft structure of the strain gauge. To improve the control performance, the observer technique is proposed to estimate the external force without force sensor.

Acceleration Sensor based Load Side Disturbance Observer (ALDOB)

3.1 ALDOB for Two mass system

In this research, a new combined observer technique, named acceleration sensor based load side disturbance observer (ALDOB), has been proposed by using acceleration sensor and optical encoder. Applying an acceleration sensor scheme is an alternative way to supply the movement information of load side to a disturbance observer. Instead of using optical encoder to measure position response at the load side, an acceleration sensor is used to measure acceleration information from the end-effectors. Since acceleration sensors can be implemented in a small area on the load side, it is considered to be suitable for the real applications. The method to estimate the external force at the load side is obtained from the Kalman filter, disturbance observer and a simple first-order low-pass filter as follows,

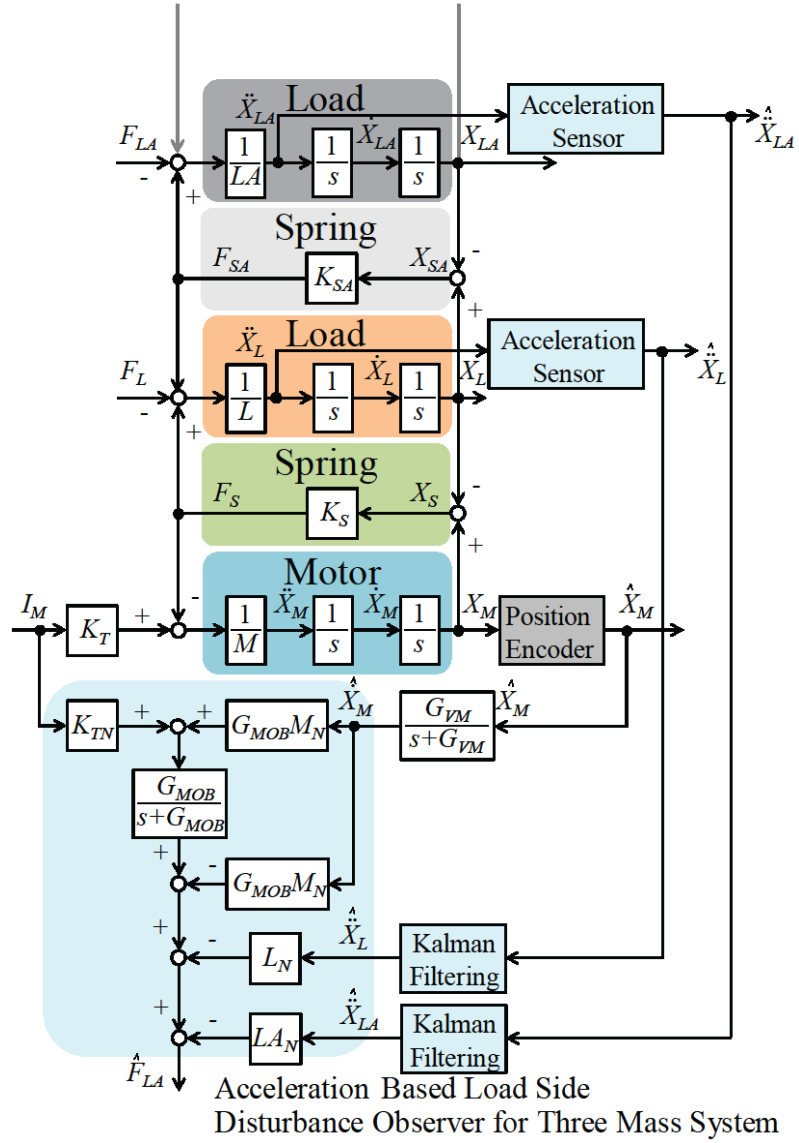


Fig. 4. Schematic diagram of Acceleration Sensor based Load Side Disturbance Observer for three mass system

$$\hat{\ddot{F}}_L = \left(\frac{G_{MOB}}{s + G_{MOB}} \left(K_{TN} I_M + G_{MOB} M_N \hat{\dot{X}}_M \right) - G_{MOB} M_N \hat{\dot{X}}_M - L_N \hat{\ddot{X}}_L \right) \quad (8)$$

where K_{TN} and M_N refer to the nominal force coefficient and the nominal motor mass, respectively. $\dot{X}_M$ is the velocity of motor side. G_{MOB} is the cut-off frequency of the observer; L_N and $\dot{X}_L$ are the nominal load mass and the acceleration of load side, respectively.

3.2 ALDOB for Three mass system

Such techniques can also apply in the flexible robot based on multi-mass system as shown in Fig. 4. In this section, a specially designed of acceleration based load-side disturbance observer that can be used to estimate the external force of multi-mass system is analyzed. The dynamic equation of the upper part of three-mass system is described by,

$$\ddot{X}_{L_A} = \frac{K_{SA}}{L_A} X_{SA} - \frac{1}{L_A} F_{L_A}, \quad (9)$$

$$\dot{X}_{SA} = \dot{X}_L - \dot{X}_{L_A} \quad (10)$$

where A denotes the parameters of the third mass.

The total external force on the load side F_{L_A} without the vibration effect can be estimated as

$$F_{L_A} = K_{TN} I_M - M_N \ddot{X}_M - L_N \ddot{X}_L - L_{AN} \ddot{X}_{L_A} \quad (11)$$

$$\hat{F}_{L_A} = \left(\frac{G_{MOB}}{s + G_{MOB}} \left(K_{TN} I_M + G_{MOB} M_N \hat{X}_M \right) - G_{MOB} M_N \hat{X}_M - L_N \hat{X}_L - L_{AN} \hat{X}_{L_A} \right) \quad (12)$$

As shown in Fig. 3 and 4, the Kalman-filter is applied to compensate the unwanted white Gaussian noise of the acceleration signal. The process of the Kalman-filter consisting of the operation in two phases: prediction and update. Using a Kalman filter, the state-space formulation of the measured acceleration signal can be expressed as

$$\mathbf{x}_{(k+1)} = \mathbf{A}_{(k)} \mathbf{x}_{(k)} + \mathbf{B}_{(k)} \mathbf{u}_{(k)} + \mathbf{w}_{(k)} \quad (13)$$

$$\mathbf{z}_{(k)} = \mathbf{C}_{(k)} \mathbf{x}_{(k)} + \mathbf{v}_{(k)} \quad (14)$$

where k represents the sampling instant, $\mathbf{x}_{(k)}$ is the vector of states, $\mathbf{u}_{(k)}$ is the vector of input variables, $\mathbf{A}_{(k)}$ and $\mathbf{B}_{(k)}$ are system matrices, $\mathbf{C}_{(k)}$ is the measurement matrix, $\mathbf{z}_{(k)}$ is the vector of measured variables, $\mathbf{w}_{(k)}$ is the process noise and $\mathbf{v}_{(k)}$ represents the measurement which is corrupted by white Gaussian noise. It is assumed that the covariance matrix of the process $\mathbf{Q}$, the covariance matrices of the measurement noise $\mathbf{R}$ and the cross-covariance matrix are as given below:

$$\mathbf{Q} = E\{\mathbf{w}\mathbf{w}^T\} > 0 \quad (15)$$

$$\mathbf{R} = E\{\mathbf{v}\mathbf{v}^T\} \geq 0 \quad (16)$$

$$E\{\mathbf{w}\mathbf{v}^T\} = 0 \quad (17)$$

The matrices $\mathbf{Q}$ and $\mathbf{R}$ are used to tune the accuracy and response of the observer, and these values can be determined by using the simulations for the testing of the measurement sensors. A compromise between the performance of observer and the compensation of acceleration signal noise can be found. The Kalman filter estimation and updating equations for signal enhancement are as follows:

$$\mathbf{x}_{(k|k-1)} = \mathbf{A}_{(k-1)} \mathbf{x}_{(k-1|k-1)} + \mathbf{B}_{(k-1)} \mathbf{u}_{(k-1)} \quad (18)$$

$$\mathbf{P}_{(k|k-1)} = \mathbf{A}_{(k-1)} \mathbf{P}_{(k-1|k-1)} \mathbf{A}_{(k-1)}^T + \mathbf{Q}_{(k-1)} \quad (19)$$

$$\mathbf{S}_{(k)} = \mathbf{C}_{(k)} \mathbf{P}_{(k|k-1)} \mathbf{C}_{(k)}^T + \mathbf{R}_{(k)} \quad (20)$$

$$\mathbf{M}_{(k)} = \mathbf{P}_{(k|k-1)} \mathbf{C}_{(k)}^T \mathbf{S}_{(k)}^{-1} \quad (21)$$

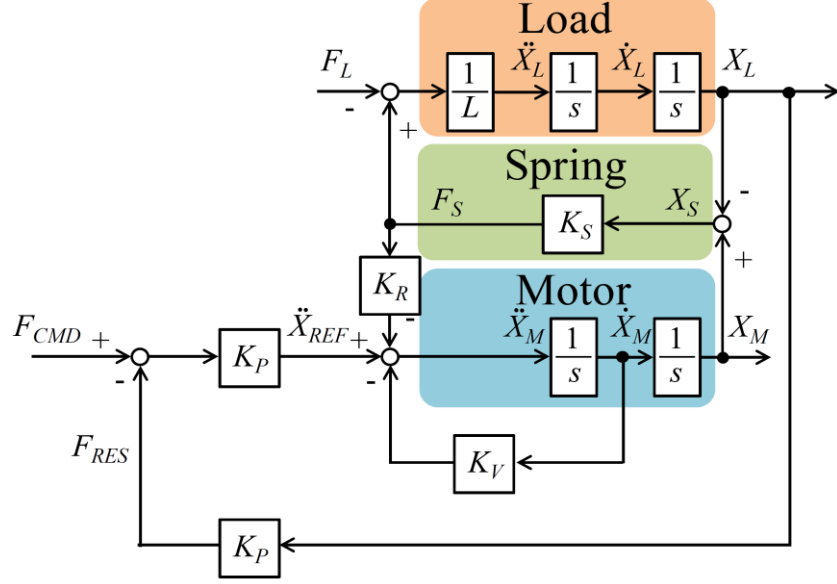


Fig. 5. The simplified block diagram of the resonance ratio control for two mass system

$$\mathbf{x}_{(k|k)} = \mathbf{x}_{(k|k-1)} + \mathbf{M}_{(k)}(\bar{\mathbf{z}}_{(k)} - \mathbf{C}_{(k)}\mathbf{x}_{(k|k-1)}) \quad (22)$$

$$\mathbf{P}_{(k|k)} = \mathbf{P}_{(k|k-1)} - \mathbf{M}_{(k)}\mathbf{S}_{(k)}\mathbf{M}_{(k)}^T \quad (23)$$

where $\mathbf{P}$ is the error covariance matrices. $\mathbf{M}$ and $\mathbf{S}$ are the Kalman filter gain matrix and the total uncertainty measurement of matrix, respectively $\mathbf{z}_{(k)}$ is an actual measurement of acceleration sensor which is updated the estimated state vector and the error matrix at every sampling instant.

4. Controller Design of Flexible Robot System

4.1 Resonance Ratio Control Based on CDM for Two-Mass System

In recent years, advances in motion control technologies have brought significant rapid growth to machine and robot development. A conventional PID controller exhibits good controlling ability and improvement on its output response. However, PID controller cannot perform well in the machine with vibration effects.

This leads to the development of more effective controller design to reduce the vibration effects. Yuki et al. have developed a resonance ratio control that can be applied with disturbance observer to suppress the oscillation during task executions for a torsional vibration in the position control by feeding back the estimated reaction torque on the motor side. Thus, it is possible to change the resonance frequency of the system to an arbitrarily value. This idea is used later by Katsura et. al to design sensorless force controller.

The control structure design based on disturbance observer is less complex and more efficient as shown in Fig. 5. The force controller based on resonance ratio control consists of a force gain K_P , a velocity gain K_V and a reaction force gain K_R . The feedback force will depend on the force contact on the robot by known environment stiffness K_E .

From Fig. 5, the transfer functions from acceleration reference $\ddot{X}_{REF}$ to motor position X_M and motor position X_M to load position X_L can be calculated as follows,

$$\frac{\hat{X}_M}{\ddot{X}_{REF}} = \frac{Ls^2 + K_S}{Ls^4 + K_S(1 + K_RL)s^2} \quad (24)$$

$$\frac{\hat{X}_L}{\hat{X}_M} = \frac{K_S}{Ls^2 + K_S} \quad (25)$$

The new anti-resonance frequency ω_{AR} and the resonance frequency ω_R of the system can be computed as follows,

$$\omega_R = \sqrt{\frac{K_S}{L}(1 + K_RL)}, \quad (26)$$

$$\omega_{AR} = \sqrt{\frac{K_S}{L}}. \quad (27)$$

The transfer function of the force servoing based on resonance ratio control is given by,

$$\frac{F_{RES}}{F_{CMD}} = \frac{K_P K_E \omega_{AR}^2}{s^4 + K_V s^3 + \omega_R^2 s^2 + K_V \omega_{AR}^2 s + K_P K_E \omega_{AR}^2} \quad (28)$$

In this research, a new resonance ratio parameter is calculated by using the coefficient diagram method (CDM). The CDM design method is used to design the characteristic polynomial of the closed loop system by achieving a good balance of stability and good robust performance. As it is seen from equation (28), the coefficients of characteristic polynomial a_i are found as,

$$a_0 = K_P K_E \omega_{AR}^2 \quad (29)$$

$$a_1 = K_V \omega_{AR}^2 \quad (30)$$

$$a_2 = \omega_R^2 \quad (31)$$

$$a_3 = K_V \quad (32)$$

$$a_4 = 1.0 \quad (33)$$

The standard stability indices γ_i for the Manabe form are chosen as $\gamma_1 = 2.5$, $\gamma_2 = 2.0$, and $\gamma_3 = 2.0$.

$$\tau = \frac{a_1}{a_0} = \frac{K_V}{K_P K_E} \quad (34)$$

$$\gamma_1 = \frac{a_1^2}{a_0 a_2} = \frac{K_V^2 \omega_{AR}^2}{K_P K_E \omega_R^2} = 2.5 \quad (35)$$

$$\gamma_2 = \frac{a_2^2}{a_1 a_3} = \frac{\omega_R^4}{K_V^2 \omega_{AR}^2} = 2.0 \quad (36)$$

$$\gamma_3 = \frac{a_3^2}{a_2 a_4} = \frac{K_V^2}{\omega_R^2} = 2.0 \quad (37)$$

Thus, the controller parameters calculated by the design of CDM are given as follow,

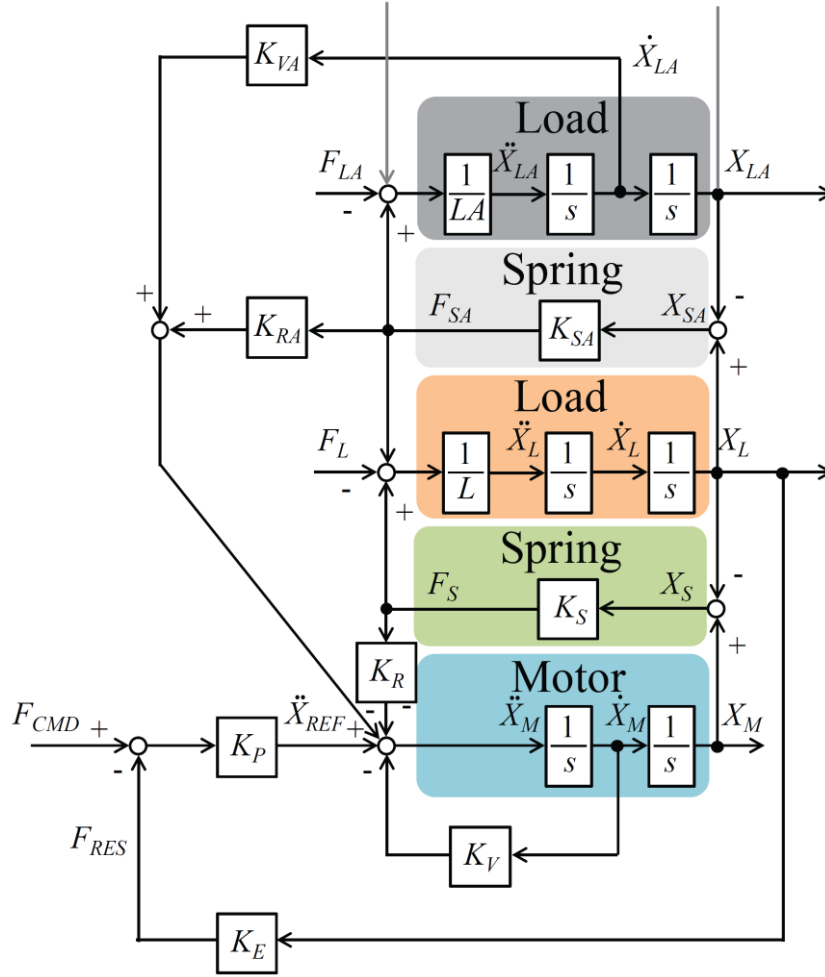


Fig. 6. The simplified block diagram of the resonance ratio control for three mass system

$$K_V = \sqrt{2}\omega_R \quad (38)$$

$$K_P = \frac{4\omega_{AR}^2}{5K_E} \quad (39)$$

$$K = \frac{\omega_R}{\omega_{AR}} = 2.0 \quad (40)$$

$$K_R = \frac{3}{L} \quad (41)$$

By setting these controller gains, a new resonance ratio parameter is chosen as 2.0.

4.2 Resonance Ratio Control Based on CDM for Three-Mass System

Similar control architecture can be implemented in the multi-mass system. The block diagram representation of a resonance ratio control for three mass systems is shown in Fig. 6. If the acceleration signals are measured by sensors, the value of external torques or forces at the end-effector side can be determined by the ALDOB. Based on this principle, the external force from the load-side could be determined and compensated with a simple multiplication of the reaction force gain K_{RA} to the motor side. From the block diagram in Fig. 6, the transfer function of the three mass systems from the force command F_{CMD} to the motor displacement X_M can be expressed as

$$\frac{X_M}{F_{CMD}} = \frac{(s^2 + \omega_{AR1}^2)(s^2 + \omega_{AR2}^2)}{Ms^2(s^2 + \omega_{R1}^2)(s^2 + \omega_{R2}^2)} \quad (42)$$

where ω_{R1} and ω_{AR1} are the first resonance and anti-resonance frequency, and ω_{R2} and ω_{AR2} are the second resonance and anti-resonance frequency. The value of the ω_{AR1} and ω_{AR2} can be defined as the following calculation:

$$\omega_{AR1}^2 + \omega_{AR2}^2 = \frac{K_S + K_{SA}}{L} + \frac{K_{SA}}{L_A} \quad (43)$$

$$\omega_{AR1}^2 \omega_{AR2}^2 = \frac{K_S K_{SA}}{L L_A} \quad (44)$$

From the block diagram in Fig. 6, the transfer function of the three mass system from the force response F_{RES} to the force command F_{CMD} can be expressed as

$$\frac{F_{RES}}{F_{CMD}} = \frac{K_P K_E \omega_{AR1}^2 \omega_{AR2}^2}{a_6 s^6 + a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0} \quad (45)$$

The coefficients of characteristic polynomial a_i are found as,

$$a_0 = K_E K_P \omega_{AR1}^2 \omega_{AR2}^2 \quad (46)$$

$$a_1 = (K_V + K_{VA}) \omega_{AR1}^2 \omega_{AR2}^2 \quad (47)$$

$$a_2 = \omega_{AR1}^2 \omega_{AR2}^2 + (L + L_A) K_R \omega_{AR1}^2 \omega_{AR2}^2 + L_A K_{RA} \omega_{AR1}^2 \omega_{AR2}^2 \quad (48)$$

$$a_3 = K_V (\omega_{AR1}^2 + \omega_{AR2}^2) \quad (49)$$

$$a_4 = \omega_{AR1}^2 + \omega_{AR2}^2 + K_{SA} K_R \quad (50)$$

$$a_5 = K_V \quad (51)$$

$$a_6 = 1 \quad (52)$$

The standard stability indices γ_i for the Manabe form are chosen as $\gamma_1 = 2.5$, $\gamma_2 = 2.0$, $\gamma_3 = 2.0$, $\gamma_4 = 2.0$ and $\gamma_5 = 2.0$.

$$\tau = \frac{a_1}{a_0} = \frac{K_V + K_{VA}}{K_P K_E} \quad (53)$$

$$\begin{aligned} \gamma_1 &= \frac{a_1^2}{a_0 a_2} \\ &= \frac{(K_V + K_{VA})^2}{K_P K_E (1 + (L + L_A) K_R + L_A K_{RA})} = 2.5 \end{aligned} \quad (54)$$

$$\begin{aligned} \gamma_2 &= \frac{a_2^2}{a_1 a_3} \\ &= \frac{\omega_{AR1}^2 \omega_{AR2}^2 (1 + (L + L_A) K_R + L_A K_{RA})^2}{K_V (K_V + K_{VA}) (\omega_{AR1}^2 + \omega_{AR2}^2)} = 2.0 \end{aligned} \quad (55)$$

$$\begin{aligned}
\gamma_3 &= \frac{a_3^2}{a_2 a_4} \\
&= \frac{K_V^2 (\omega_{AR1}^2 + \omega_{AR2}^2)}{\omega_{AR1}^2 \omega_{AR2}^2 (1 + (L + L_A) K_R + L_A K_{RA})} \\
&\quad \times \frac{1}{(\omega_{AR1}^2 + \omega_{AR2}^2 + K_S K_R)} = 2.0
\end{aligned} \tag{56}$$

$$\begin{aligned}
\gamma_4 &= \frac{a_4^2}{a_3 a_5} \\
&= \frac{(\omega_{AR1}^2 + \omega_{AR2}^2 + K_S K_R)^2}{K_S K_R (\omega_{AR1}^2 + \omega_{AR2}^2)} = 2.0
\end{aligned} \tag{57}$$

$$\begin{aligned}
\gamma_5 &= \frac{a_5^2}{a_4 a_6} \\
&= \frac{K_V^2}{\omega_{AR1}^2 + \omega_{AR2}^2 + K_S K_R} = 2.0
\end{aligned} \tag{58}$$

Thus, the controller parameters calculated by the design of CDM are given as follow,

$$K_V = \sqrt{8(\omega_{AR1}^2 + \omega_{AR2}^2)} \tag{60}$$

$$K_{VA} = \frac{\sqrt{8(\omega_{AR1}^2 + \omega_{AR2}^2)}((\omega_{AR1}^2 + \omega_{AR2}^2)^2 - 16\omega_{AR1}^2 \omega_{AR2}^2)}{16\omega_{AR1}^2 \omega_{AR2}^2} \tag{61}$$

$$K_R = \frac{3(\omega_{AR1}^2 + \omega_{AR2}^2)}{K_S} \tag{62}$$

$$K_{RA} = \frac{K_S(\omega_{AR1}^2 + \omega_{AR2}^2) - \omega_{AR1}^2 \omega_{AR2}^2 (K_S + 3(L + L_A))}{K_S(L + L_A)\omega_{AR1}^2 \omega_{AR2}^2} \tag{63}$$

$$K_P = \frac{LK_S A^2 \sqrt{8A}}{40K_E(L_A K_S(A^2 - B) + LB(K_S + 3(L_A - L_A)))} \tag{64}$$

where

$$A = \omega_{AR1}^2 + \omega_{AR2}^2, B = \omega_{AR1}^2 \omega_{AR2}^2 \tag{65}$$

5. Feedforward load disturbance compensation

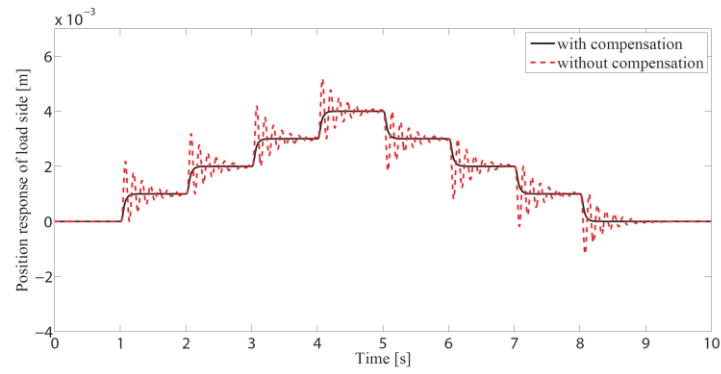
5.1 Feedforward load disturbance compensation for two mass system

The block diagram of the proposed control structure is shown in Fig. 7. The load disturbance compensation is introduced to compute and feedback the estimated load disturbance force through the inverse system of the motor side. The inverse system can be represented by the transfer function from F_{CMD} to F_{RES} as shown in (45) and from F_L to F_{RES} as follows,

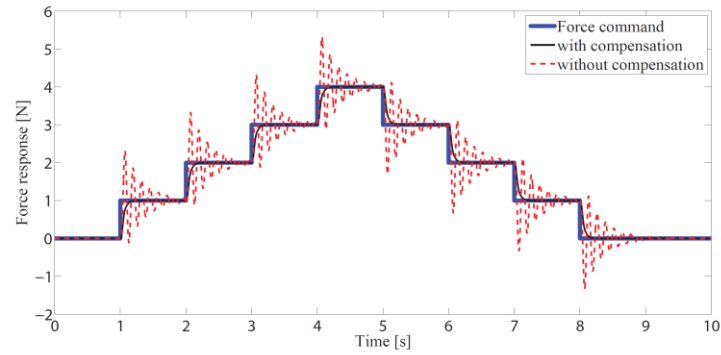
$$\frac{F_{RES}}{F_L} = \frac{\frac{1}{L} K_E (s^2 + K_V s + K_R K_S)}{s^4 + K_V s^3 + \omega_R^2 s^2 + K_V \omega_{AR}^2 s + K_P K_E \omega_{AR}^2} \tag{66}$$

Then, the inverse system can be calculated by the following equation:

$$\frac{F_{CMD}}{F_L} = \frac{s^2 + K_V s + K_R K_S}{K_P K_S} \tag{67}$$



(a)



(b)

Fig. 8. Simulation results of two mass system.

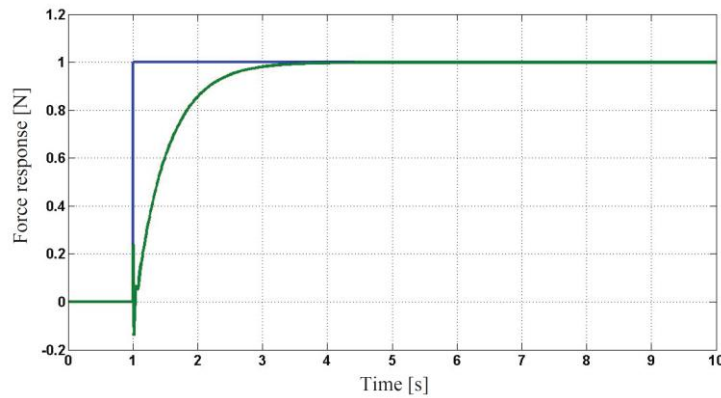


Fig. 9. Simulation results of three mass system.

For the flexible robot system having a multi mass, the proposed method can be applied and designed the controller and observer by calculating the transfer function of the multi mass system.

6. Simulation results

In order to show the validity and usefulness, numerical simulations are given to confirm of the proposed controller and observer design. The flexible robot system was simulated using MATLAB software. The results obtained from the proposed approach are compared with the results obtained from the conventional PID control. The first simulation result was conducted by using PID

TABLE I
PARAMETERS USED IN EXPERIMENTAL SETUP

Controller parameters	Symbol	Value	Units
Mass of motor	M	0.245	kg
Force constant coefficient	K_t	3.333	N/A
Mass of load	L	0.245	kg
Spring coefficient	K_{SN}	1100	N/m
Force gain	K_P	3.59	
Velocity gain	K_V	189.52	
Reaction force gain	K_R	12.24	
Resonance ratio gain	K	2	
Cut-off freq. of vel.	G_{VE}	1000	rad/s
Cut-off freq. of DOB.	G_{DIS}	1000	rad/s
Cut-off freq. of LDOB.	G_{LOB}	800	rad/s
Cut-off freq. of MEDOB.	G_{MOB}	800	rad/s

Table. 1. Parameters used in experimental setup.

controller, and the position, velocity, acceleration, and the contact force responses were collected as shown in Fig. 8. From the results, the force command input is a stepwise function. It is seen from Fig. 8 (b) that without reaction force compensation feedbacks give a poor response with a very large vibration. On the other hand, the vibration is well compensated in the case of the resonance ratio control. It is clear from these results that the resonance ratio control based on CDM design approach gives a good response with no overshoot and short settling time compared to the conventional PID controller design.

Extending from our proposed method, the resonance ratio control based on three mass systems was tested. The input step function is used as the force command. From Fig. 9, it is also confirmed that the resonance ratio control can compensate for vibration effect of the contact force response completely.

7. Experimental Results

This section describes experimental implementation of resonance ratio control using ALDOB in real conditions, and the contact force response, the speed and position of motor and load were being investigated. The control algorithm was implemented in a PC using RT-Linux with a sampling time of 100 μs . A summary of the parameters used in the experiment and the specification of sensors are presented in Table I and Table II, respectively. To verify the proposed observer and controller design of the flexible robot system, an acceleration sensor and linear optical encoder were implemented in the experimental feedback control system as shown in Fig. 10. The acceleration sensor was mounted on a linear motor at the load side, which has an optical encoder installed in order to observe vibration effect at the motor side and load side. The parameters in the controller were tuned to match the controller design in the identify transfer function of flexible robot system. All

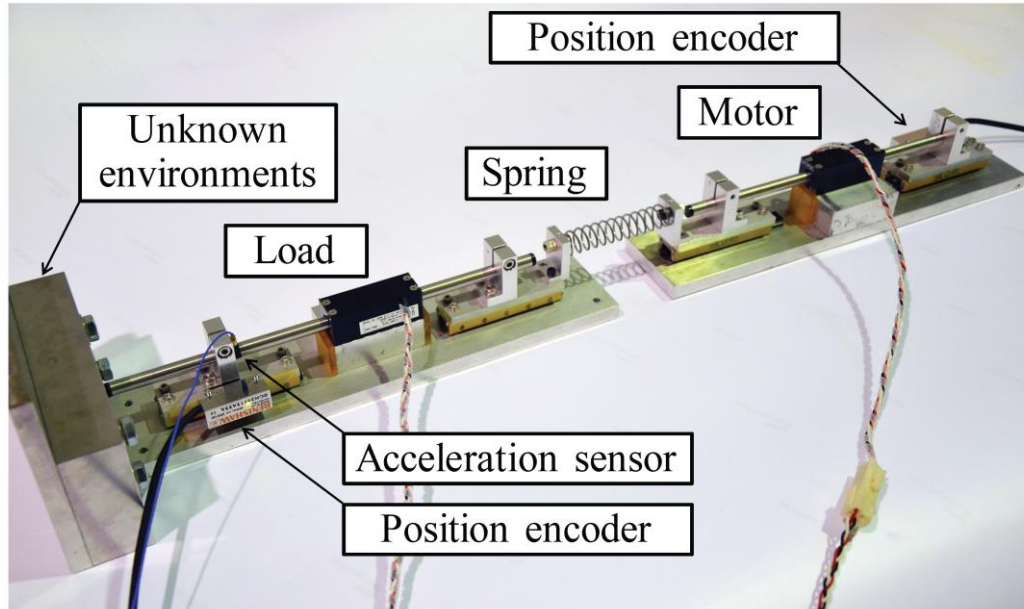


Fig. 10. Experimental setup of flexible robot system.

TABLE II
SPECIFICATION OF SENSORS

Optical encoder	Symbol	Value	Units
Resolution grade		0.1	μm
Weight		11.0	g
Dimension		$14.8 \times 36.0 \times 13.5$	mm
Maximum speed		10	m/s
Acceleration sensor	Symbol	Value	Units
Bandwidth		$1 \sim 10K$	Hz
Weight		5.0	g
Dimension		$6.4 \times 11.4 \times 3.6$	mm

Table. 2. Specification of sensors.

of the identified parameters were used to calculate the controller gain. The input stepwise is used as the force command. The control structure of resonance ratio control with a two-mass system as shown in Fig. 7 was investigated.

In the first experiment, a sponge was prepared as a sample environment for the test. On the other hand, an aluminum block was set at the end-effector in the second experiment. The aluminum block is usually stiffer than the sponge. It was embedded close to the end-effector of the robot. The responses of motor side and load side are shown in Figures 11 (a), (b) and 12 (a), (b) and the responses of the contact force estimation by using ALDOB and LDOB are shown in Fig. 11 (f) and 12 (f). Without the vibration compensation, it is found that the responses of position at the motor side and load side are oscillated. The influence of the reaction force feedback can be observed to

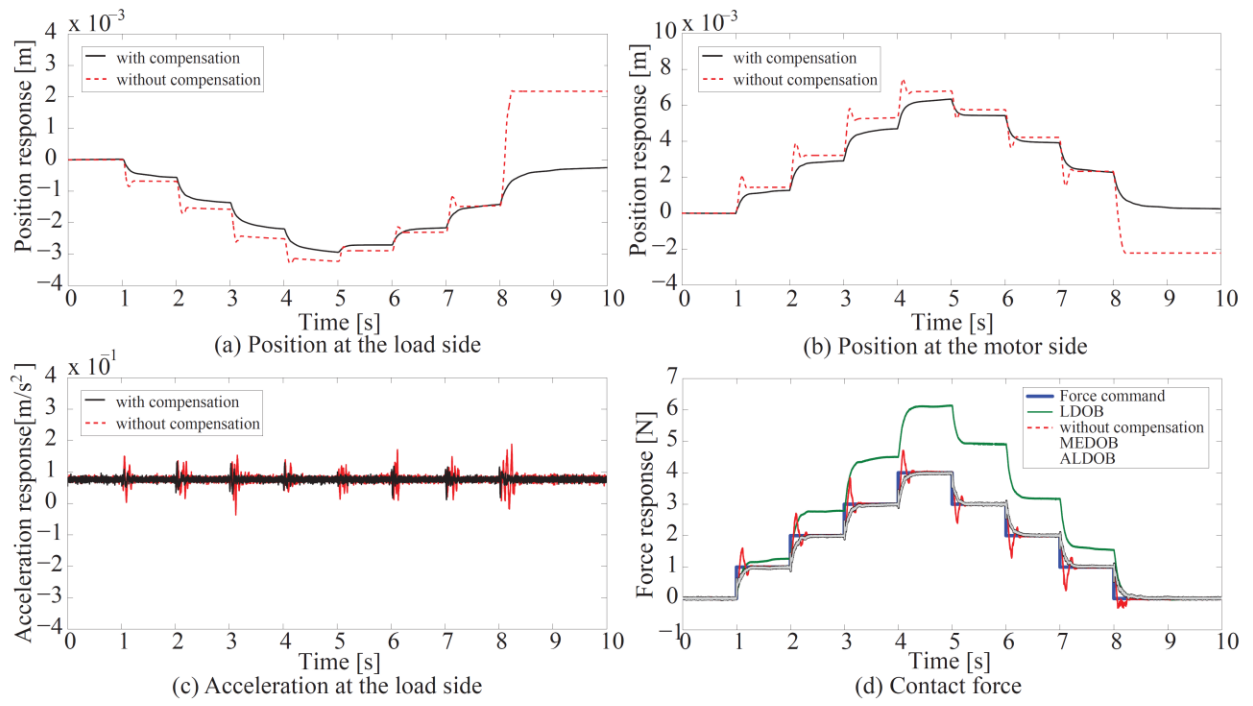


Fig. 11. Experimental results of linear motor in contact with a sponge.

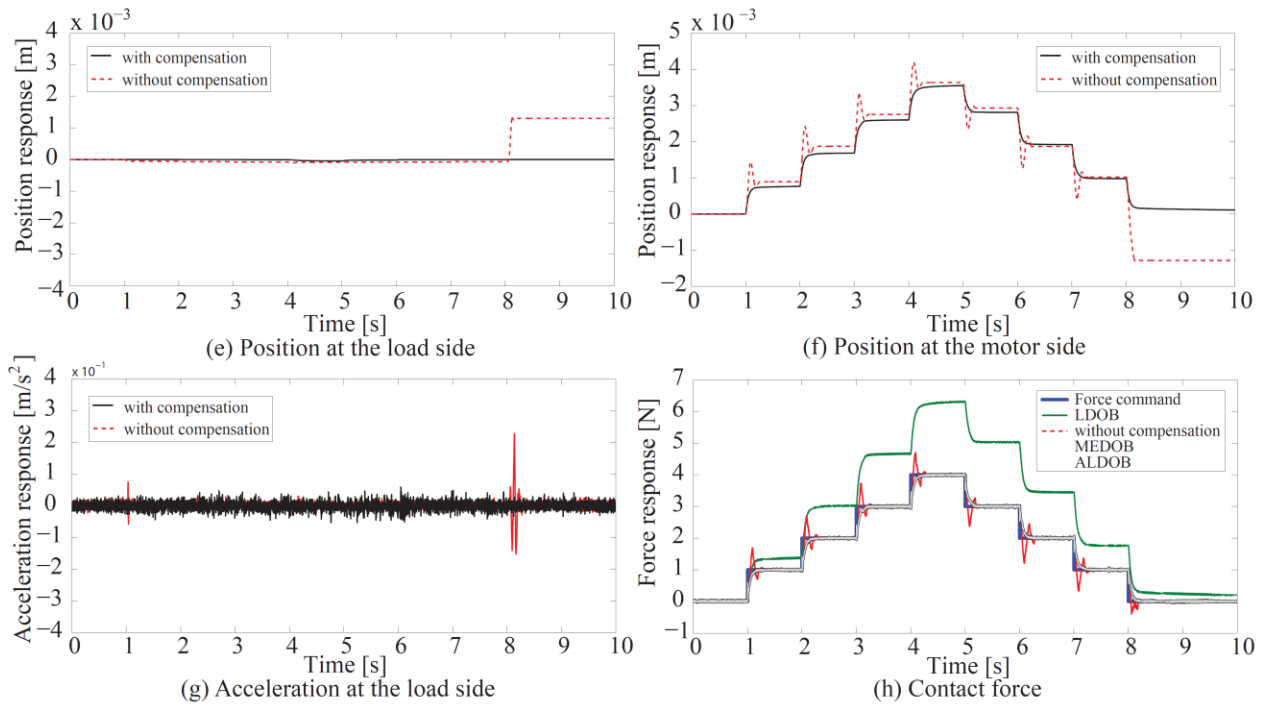


Fig. 12. Experimental results of linear motor in contact with an aluminum block.

significantly reduced the effective vibration by using the resonance ratio control. The improvement in the position and responses at the motor side and load side are illustrated. During the test, the contact force estimation using ALDOB were checked to confirm they matched the contact force estimation using MEDOB during experiments. By using LDOB, the mismatched value of the spring coefficient K_s caused incorrect estimation in the contact force response. If the spring coefficient is accurately identify, the force estimation can be improved the accuracy of the force estimation.

Figure 11 (f) and 12 (f) show the force response without and with compensator. The controller without the reaction force feedback compensation was chosen to illustrate the worst-case vibration. Based on the force estimation recorded during the test, the system force of the proposed method followed the reference command with only a small tracking error. By using the proposed resonance ratio control with ALDOB, it is observed that the oscillation in the contact force response were small. The spring vibrations were significantly reduced in the contact force response. It was shown that the resonance ratio control can suppress the oscillation more effectively than a conventional PID control.

8. Conclusion and future work

In this research, we described how acceleration sensor was integrated with ALDOB to estimate and control the contact force. Since acceleration sensors can be implemented in a small area on the load side, it is considered to be suitable for the real applications. The proposed ALDOB observer can be utilized with resonance ratio control to suppress high-frequency vibrations of spring. Since the optimal parameters are designed by using coefficient diagram method, the resonance ratio control can ensure good robustness of the force control. We performed this analysis for two types of systems, the two mass systems and three mass systems, which are representative of many physical systems. Moreover, this proposed approach could also be applied for other multi mass system. The obtained simulation and experimental results confirmed the efficiency of the proposed resonance ratio control with ALDOB for the robust force control system without use of force sensors.

9. Acknowledgment

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Output จากโครงการวิจัยที่ได้รับทุนจาก สกว.

1. ผลงานตีพิมพ์ในวารสารวิชาการนานาชาติ (ระบุชื่อผู้แต่ง ชื่อเรื่อง ชื่อวารสาร ปี เล่มที่ เลขที่ และหน้า) หรือผลงานตามที่คาดไว้ในสัญญาโครงการ

International journal

- (1) C. Mitsantisuk, and K. Ohishi, "Vibration Compensation of Flexible Robot Using Resonance Ratio Control with Acceleration Sensor Based Load Side Disturbance Observer," IEEE Transactions on Industrial Electronics, vol. --, no. --, pp. ---, (Major revision) (Quartile 1)
 - (2) C. Mitsantisuk, S. Stapornchaisit, "Micro-macro Bilateral Control in Delta Robot," International Review of Automatic Control, vol. --, no. --, pp. ---, (In the review process) (Quartile 2)
 - (3) N. Niramitvasu, and C. Mitsantisuk, "Bilateral Control Based on Disturbance Observer of Delta Robot with Gravity Compensation," Applied Mechanics and Materials, vol. 781, pp. 445–449, June. 2015
 - (4) (4) N. Varachitchai, and C. Mitsantisuk, "An Analysis of Force Response by Using Spectrogram," Applied Mechanics and Materials, vol. 781, pp. 466–470, June. 2015
2. การนำผลงานวิจัยไปใช้ประโยชน์
 - เชิงพาณิชย์ (มีการนำไปผลิต/ขาย/ก่อให้เกิดรายได้ หรือมีการนำไปประยุกต์ใช้โดยภาคธุรกิจ/บุคคลทั่วไป)
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 - เชิงสาธารณะ (มีเครือข่ายความร่วมมือ/สร้างกระแสมหาชนในวงกว้าง)
 -
 - เชิงวิชาการ (มีการพัฒนาการเรียนการสอน/สร้างนักวิจัยใหม่)

จากผลการดำเนินงานโครงการ "High Sensation of Haptic Feedback in Robot-Assisted Device based on Acceleration Control with Compensation of Mechanical Resonance" โดยสามารถพัฒนา ตัวสังเกตการณ์สัญญาณรบกวนซึ่งสามารถประมาณค่าแรงภายนอกออกมาได้โดยไม่ต้องใช้เซนเซอร์วัดแรง โดยตัวสังเกตการณ์สามารถเพิ่มประสิทธิภาพการทำงานจากการใช้เซนเซอร์หลายตัวผสานการทำงานร่วมกันทั้งเซนเซอร์วัดตำแหน่ง และเซนเซอร์วัดความเร่ง ระบบการควบคุมมีความคงทนต่อสัญญาณรบกวนภายนอก และลดการสั่นสะเทือนในระบบ ซึ่งโครงการนี้สามารถสร้างองค์ความรู้ใหม่ (Journal paper)

นำไปใช้ในการพัฒนาการเรียนการสอน และผลิตบุคลากรทางด้านวิศวกรรมไฟฟ้าสาขาควบคุม ทั้งปริญญาโท และ ปริญญาตรี นอกจากนี้ยังนำผลงานวิจัยดังกล่าวไปเผยแพร่ในงานประชุมวิชาการทั้งระดับชาติและนานาชาติอีกด้วย

3. อื่นๆ (เช่น ผลงานตีพิมพ์ในวารสารวิชาการในประเทศ การเสนอผลงานในที่ประชุมวิชาการ หนังสือ การจดสิทธิบัตร)

การเสนอผลงานในที่ประชุมวิชาการ ระดับนานาชาติ

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(7) S. Jarudamrongsak, C. Mitsantisuk, P. Bunnun and Y. Koike, "Robot system for rehabilitation of wrist using bilateral control based on disturbance observer", The 2014 International Electrical Engineering Congress, iEECON 2014, March 19-21, 2014, Pattaya City, Thailand, 19 - 21 March 2014, พัทยา ชลบุรี Kingdom of Thailand

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(9) P. Kladjaroen, S. Jarudamrongsak, C. Mitsantisuk and K. Hongesombut, "Vibration Suppression of Flexible Three-Mass System Using PID Controller Based on Resonance Ratio Control", The 29th International Technical Conference on Circuit/Systems Computers and Communications (ITC-CSCC 2014), 1 - 4 July 2014, ภูเก็ต Kingdom of Thailand

(10) N. Varachitchai, N. Niramitwasu, C. Mitsantisuk and W. Kanokbannakorn, "A Spectrogram Analysis of Impact Force Response in a Tele-operated Robot System", The 29th International Technical Conference on Circuit/Systems Computers and Communications (ITC-CSCC), 1 - 4 July 2014, ภูเก็ต Kingdom of Thailand

(11) C. Mitsantisuk and K. Ohishi, "Transparency Improvement in A Bilateral Motion-Scaling Control Using Kalman-Filter-Based Disturbance Observer", The 40th Annual Conference of the IEEE Industrial Electronics Society, IECON 2014, 30 October - 1 November 2014, Dallas Texas, United States of America

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**Vibration Compensation of Flexible Robot Using Resonance
Ratio Control with Acceleration Sensor Based Load Side
Disturbance Observer**

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Manuscript Type:	SS on Advanced Motion Control for Next-Generation Industrial Applications
Manuscript Subject:	
Keywords:	Motion control, Robot tactile systems, Acceleration control
Are any of authors IEEE Member?:	Yes
Are any of authors IES Member?:	Yes

Vibration Compensation of Flexible Robot Using Resonance Ratio Control with Acceleration Sensor Based Load Side Disturbance Observer

Abstract—This paper proposes a specially designed acceleration sensor based load side disturbance observer (ALDOB) with Kalman filtering technique that can be used to estimate the external force on the load side for multi mass system. The proposed observer employs an acceleration sensor and optical encoder to perform contact force measurement. Since acceleration sensors can be implemented in a small area on the end-effector, it is considered to be suitable for the real applications. By using the proposed observer, it is not necessary to identify the nominal spring coefficient.

In the sensorless force control loop, the proposed ALDOB observer can be utilized with resonance ratio control to suppress high-frequency vibrations of spring. Since the optimal parameters are designed by using coefficient diagram method (CDM), the resonance ratio control can ensure good robustness of the force control. The parameters of resonance ratio control for two mass system and three mass system, which are representative of many physical systems are also analyzed. Moreover, this proposed approach could also be applied for other multi mass system.

Our experimental results of the controller's performance including its vibration were in good accord with theory and simulations. By using the proposed resonance ratio control based on the CDM, the results for the faster response without overshoot is obtained. The vibration on the system can be rejected very successfully. Moreover, the time response of the controlled closed loop system has a small settling time and the system is high robustness against the parameter variations and disturbance effects.

Index Terms— Acceleration sensor, disturbance observer, external force estimation, Kalman filter, multi mass system, flexible robot system, vibration suppression, sensor integration system, sensorless force control.

I. INTRODUCTION

ROBOTIC systems are being built to replace humans in the assistance of performing those repetitive and dangerous tasks which humans are unable to do. For example, industrial robot has been built to perform a task such as pick and place, welding, assembly, painting and product inspection. Robots can probably perform better than a human, because the robot can move more uniformly and more consistently. In the future development of robots, these robots are required to have an ability to accommodate the interaction potential with human operator [1]–[4].

Force control plays a very important role in the development of robot systems. Recently, several proposed techniques have paid attention to develop force control system and implemented force sensors to detect the external force [5]–[7]. One problem of the using force sensor devices is that they are designed to contact the environment by using strain gauge at the end-effector. As a result, the vibration noise can occur significantly from the soft structure of the strain gauge. To

improve the control performance, the observer technique is proposed to estimate the external force without force sensor. Many research have involved this techniques in order to reduce the complicity of the overall control system and increase their stability as shown in [8].

Consequently, a disturbance observer has been used, not only for improving the robustness and bandwidth of the control system, but also for estimation the external force for examples, [8]–[11]. It has been confirmed that a robust force control can be obtained, when a disturbance observer is implemented as the feed forward control for a disturbance force compensation loop. Disturbance observer offers several advantages over conventional force sensor devices. The most important advantage is that the force bandwidth can be enlarge much higher than the conventional force control with force sensor devices. Unfortunately the disturbance observer posed some challenges that remained unsolved. If such disturbance observer is to be used in a two-mass system with mechanical resonance, the instability and vibration effects can occur and degrade the overall performance. Usually, geared device is applied to increase the torque and reduces the speed of the robot's actuators. It can change the speed direction and torque conversions from a actuator to another device. By using geared devices, the motor with gear system is considered as two mass system. As a result, vibration effect from disturbance observer is occurred due to the mechanical resonance [12]–[14].

To address these problems, a load disturbance observer (LDOB) [12], which is composed of the nominal spring coefficient, the nominal load mass and the load-side encoder, has been proposed. If the spring coefficient is accurately identify, the force estimation can be easily determined. However, the exact parameters of the spring coefficient is difficult to obtain.

A multi encoder based disturbance observer (MEDOB) [14]–[15] has been proposed and applied to estimate the external force on the load side, rather than using the load side disturbance observer (LDOB) or force sensor. Since the position of the load side can be obtained, parameters identification of spring coefficient is not required. However, the MEDOB cannot be easily implemented in the real applications due to the size of the optical encoder. It is very difficult to attached the position encoder on the end-effector side.

In this research, a new combined disturbance observer with Kalman filtering technique [16]–[18], named acceleration sensor based load side disturbance observer (ALDOB), has been proposed by using acceleration sensor and optical encoder. Applying an acceleration sensor [19] scheme is an alternative way to supply the movement information of load side to a disturbance observer. Instead of using encoder to measure

position response at the load side, an acceleration sensor is used to measure acceleration information from the end-effectors. Since acceleration sensors can be implemented in a small area on the load side, it is considered to be suitable for the real applications.

Several control structures have been developed to compensate vibration effects [20]–[23]. In this paper, the proposed ALDOB observer can be utilized with resonance ratio control to suppress high-frequency vibrations of spring. Since the optimal parameters is designed by using coefficient diagram method (CDM), the resonance ratio control can ensure good robustness of the force control. The parameters of resonance ratio control for two mass system and three mass system, which are representative of many physical systems are also analyzed. Moreover, this proposed approach could also be applied for other multi mass system. From the simulation and experimental results, it is observed that the oscillation in the contacted force response were small. The spring vibrations were significantly reduced in the contacted force response.

II. MODELING OF FLEXIBLE ROBOT SYSTEM

Generally, the mechanics of machine and robot system often consist of a motor M and a load L connected by a flexible structure to transmit the actuator torque to a distant joint as shown in Fig. 1. Since the actuator is connected to the load side with a transmission mechanism, its elasticity causes resonance in the system. Therefore, the elasticity of flexible robot is realized under assumptions that it can be modeled by spring coefficient K_S and mass system [12]–[14]. A block diagram of the linear motor with two-mass system that controls under the ideal current source is shown in Fig. 2. The dynamic equation of the linear motor is described by:

$$\ddot{X}_M = -\frac{K_S}{M}X_S + \frac{K_T}{M}I_M, \quad (1)$$

$$\ddot{X}_L = \frac{K_S}{L}X_S - \frac{1}{L}F_L, \quad (2)$$

$$\dot{X}_S = \dot{X}_M - \dot{X}_L \quad (3)$$

where subscripts M and L denote the motor side and load side, respectively. F_S and F_L are the spring force and the external force on the load side. K_T is the force coefficient, I_M is the current, X_S is the torsional position from the position of the motor X_M and the position of the load X_L , M and L denote the equivalent mass of the linear motor and load mass, respectively. Naturally, this flexible transmission can negatively affects the overall performance in terms of increased vibrations.

From Fig. 2, the transfer function from current reference I_M to the velocity of motor side $\dot{X}_M$ and the transfer function from current reference I_M to the velocity of load side $\dot{X}_L$ can be calculated as follows,

$$\frac{\dot{X}_M}{I_M} = \frac{\frac{K_T}{M}(s^2 + \frac{K_S}{L})}{s^3 + (\frac{K_S}{L} + \frac{K_S}{M})s}, \quad (4)$$

$$\frac{\dot{X}_L}{I_M} = \frac{\frac{K_T K_S}{ML}}{s^3 + (\frac{K_S}{L} + \frac{K_S}{M})s}. \quad (5)$$

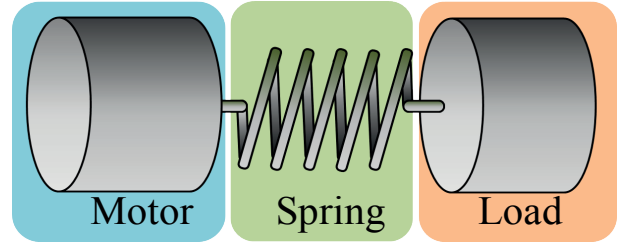


Fig. 1. Modeling of two mass system.

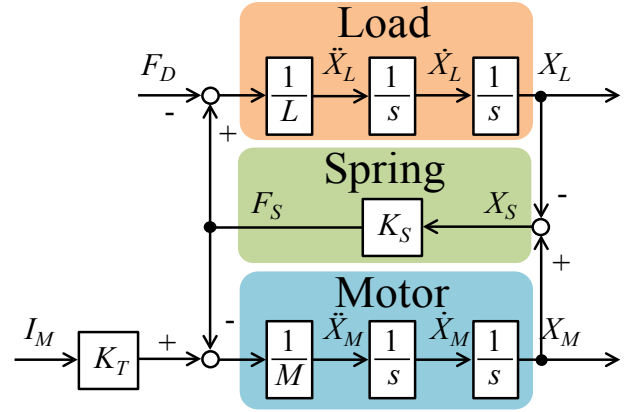


Fig. 2. The block diagram of two mass system.

Then, the anti-resonance ω_{AR} and resonance frequencies ω_R can be described as follows,

$$\omega_R = \sqrt{\frac{K_S}{L} + \frac{K_S}{M}}, \quad (6)$$

$$\omega_{AR} = \sqrt{\frac{K_S}{L}}. \quad (7)$$

III. OBSERVER BASED EXTERNAL FORCE ESTIMATION

One problem of the using force sensor devices is that they are designed to contact the environment by using strain gauge at the end-effector. As a result, the vibration noise can occur significantly from the soft structure of the strain gauge. To improve the control performance, the observer technique is proposed to estimate the external force without force sensor.

A. Disturbance Observer

A disturbance observer [8]–[11] approach instead of a force sensor [5]–[6] appeared to be a strong candidate for estimating the external force. The use of the disturbance observer thus significantly improves the bandwidth of the force estimation. From the overall schematic of the disturbance observer in Fig.3, assuming that the influence of the friction force is very small by using a small-size of linear motor in this research, the disturbance force on the motor side F_D is defined as,

$$F_D = F_{FM} + D_M \dot{X}_M + F_S + \Delta M \ddot{X}_M + \Delta K_T I_M \quad (8)$$

where, the resistive force which the direction is opposite to the motor force is the summation of friction force F_{FM} ,

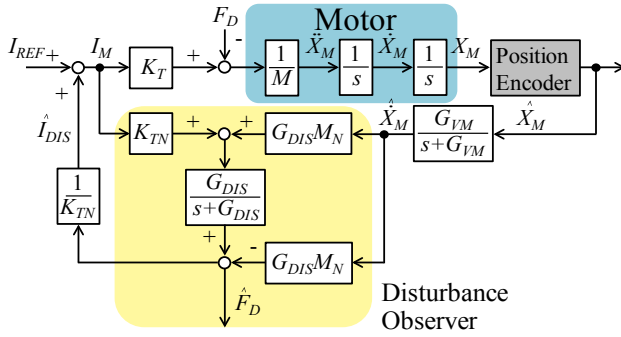


Fig. 3. Schematic diagram of disturbance observer.

viscous friction $D_M \dot{X}_M$ and the spring force F_S . $\Delta M \ddot{X}_M$ is the variation torque due to changed mass, $\Delta K_T I_M$ is the force ripple due to space harmonics. Using a block diagram analysis, disturbance observer is an external disturbance estimation algorithm that is based upon motor current and velocity information as shown in

$$\hat{F}_D = \frac{G_{DIS}}{s + G_{DIS}} \left(K_{TN} I_M + G_{DIS} M_N \hat{X}_M \right) - G_{DIS} M_N \hat{X}_M \quad (9)$$

$$\hat{X}_M = \frac{s G_{VM}}{s + G_{VM}} \hat{X}_M \quad (10)$$

where K_{TN} and M_N are refer to the nominal force coefficient and the nominal motor mass, respectively. G_{DIS} is the cut-off frequency of the disturbance observer, G_{VM} is the cut-off frequency of the motor velocity estimation. Most observers are carefully designed to be achieve the best possible performance of signal strengths according to the noise limitation. To achieve low-noise performance, the low-pass filter should be designed to have low frequency signal. With a low-pass cutoff frequency, noise is filtered out. However, the bandwidth in the force measurement can be significantly deteriorated. To apply in the real controller, accurate measured data of velocity is required to provide high accurate force sensing of disturbance observer. Moreover, the inner feed-forward disturbance compensation loop with gain $\frac{1}{K_{TN}}$ could be used to achieve high robustness force control. Disturbance observer offers several advantages over conventional force sensor devices. The first advantage is that the low-vibration performance of the force estimation can be achieved since the structure of the strain gauge in the force sensor has low stiffness. Furthermore, the force control is very high robustness due to rejecting of the disturbance force on the motor side. The most important advantage is that the force bandwidth can be enlarge much higher than the conventional force control with force sensor devices. Unfortunately the disturbance observer posed some challenges that remained unsolved. If such disturbance observer is to be used in a two-mass system with mechanical resonance, the instability and vibration effects can occur and degrade the overall performance.

B. Load Side Disturbance Observer

To address these problems, a load disturbance observer (LDOB) [12], which is composed of the nominal spring

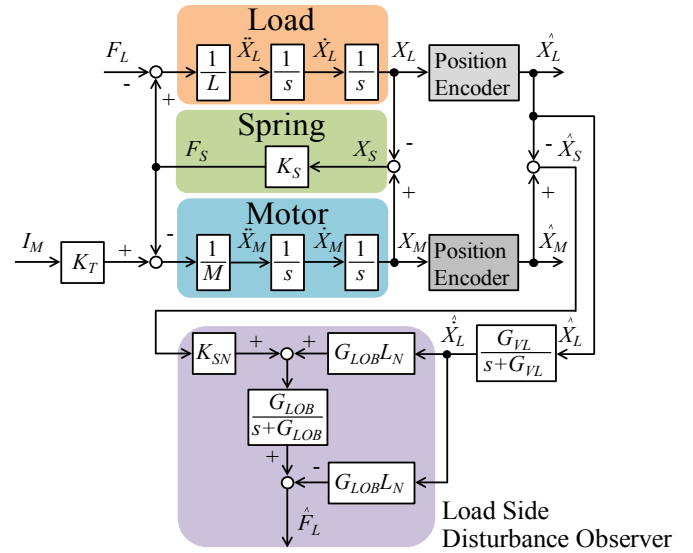


Fig. 4. Schematic diagram of load side disturbance observer.

coefficient K_{sn} , the nominal load mass L_n and the load-side encoder, has been proposed as follows,

$$F_L = K_S X_S - L_N \ddot{X}_L \quad (11)$$

$$\hat{F}_L = \left(\frac{G_{LOB}}{s + G_{LOB}} \left(K_{SN} (\hat{X}_L - \hat{X}_M) + G_{LOB} L_N \hat{X}_L \right) - G_{LOB} L_N \hat{X}_L \right) \quad (12)$$

$$\hat{X}_L = \frac{s G_{VL}}{s + G_{VL}} \hat{X}_L \quad (13)$$

where G_{VL} and G_{LOB} are the cut-off frequency of the load velocity estimation and the LDOB, respectively.

The structure of LDOB as described in this section can be shown in Fig. 4. The external force on the load side was calculated from the amounts of the current applied to the motor with the parameters identification of the two-mass system. Although, this method offers a simple way for measuring the force on the load side, it does not provide a very accurate estimation since the exact parameters of the spring coefficient is difficult to obtain and it can be assumed by a non-linear relationship. Appropriate parameters identification of the system can help to increase accuracy of the sensing scheme.

C. Multi-Encoder Based Disturbance Observer (MEDOB)

An alternative way to develop a disturbance observer is to use the measurement devices on the load side. A novel multi-encoder-based disturbance observer (MEDOB) [14]–[15] has been proposed for estimating the external force at the load side of flexible robot as shown in Fig. 5. The MEDOB consists of two optical encoders, which are attached at the motor side and the load side. The information which is necessary for the estimation of the force at the end-effector such as velocity response of motor and load are supplied to a disturbance observer. The method to estimate the external force at the load

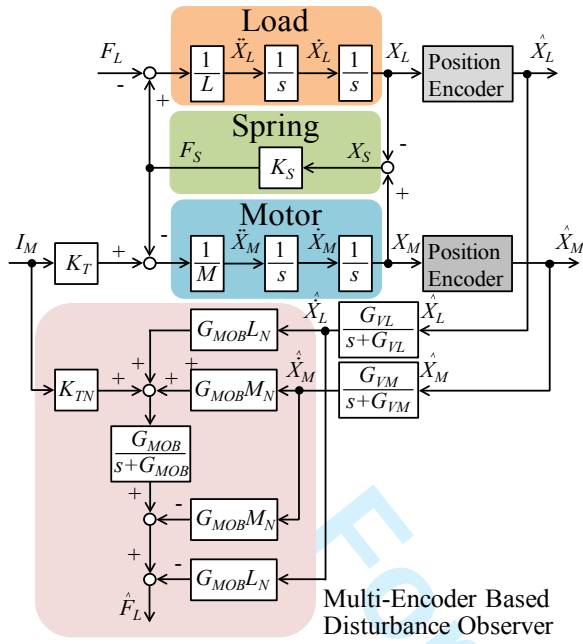


Fig. 5. Schematic diagram of multi-encoder based disturbance observer.

side is obtained from the equation (14), (15) and a simple first-order low-pass filter as follows,

$$F_L = K_{TN}I_M - M_N\ddot{X}_M - L_N\ddot{X}_L \quad (14)$$

$$\hat{F}_L = \left(\frac{G_{MOB}}{s + G_{MOB}} \left(K_{TN}I_M + G_{MOB}M_N\hat{\dot{X}}_M \right) + G_{MOB}L_N\hat{\dot{X}}_L - G_{MOB}M_N\hat{\dot{X}}_M - G_{mob}L_N\hat{\dot{X}}_L \right) \quad (15)$$

where G_{MOB} is the cut-off frequency of the MDOB. Compared to the other conventional ways such as state observer and LDOB, the proposed observer based on multi-encoder system offers the advantages of faster response, and high accuracy. Since the position of the load side can be obtained, parameters identification of spring coefficient is not required. However, the MEDOB cannot be easily implemented in the real applications due to the size of the optical encoder. It is very difficult to attached the position encoder on the end-effector side.

D. Acceleration Sensor based Load Side Disturbance Observer (ALDOB)

1) *ALDOB for Two mass system:* In this research, a new combined observer technique, named acceleration sensor [19] based load side disturbance observer (ALDOB), has been proposed by using acceleration sensor and optical encoder. Applying an acceleration sensor scheme is an alternative way to supply the movement information of load side to a disturbance observer. Instead of using optical encoder to measure position response at the load side, an acceleration sensor is used to measure acceleration information from the end-effectors. Since acceleration sensors can be implemented in a small area on the load side, it is considered to be suitable for the real applications. The method to estimate the external

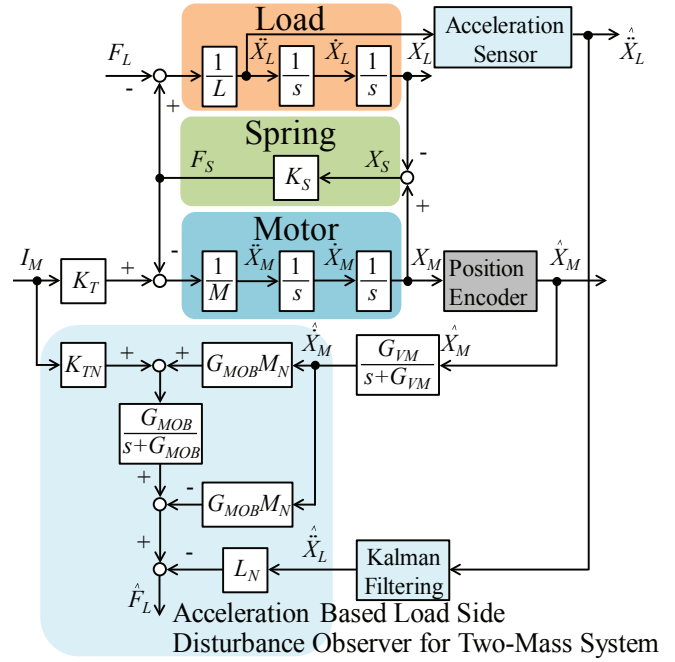


Fig. 6. Schematic diagram of acceleration load side disturbance observer for two-mass system.

force at the load side is obtained from the Kalman filter [16]–[18], disturbance observer and a simple first-order low-pass filter as follows,

$$\hat{F}_L = \left(\frac{G_{MOB}}{s + G_{MOB}} \left(K_{TN}I_M + G_{MOB}M_N\hat{\dot{X}}_M \right) - G_{MOB}M_N\hat{\dot{X}}_M - L_N\hat{\dot{X}}_L \right) \quad (16)$$

2) *ALDOB for Three mass system:* Such techniques can also apply in the flexible robot based on multi-mass system as shown in Fig. 7. In this section, a specially designed of acceleration based load-side disturbance observer that can be used to estimate the external force of multi-mass system is analyzed. The dynamic equation of the upper part of three-mass system is described by,

$$\ddot{X}_M = -\frac{K_S}{M}X_S + \frac{K_T}{M}I_M, \quad (17)$$

$$\ddot{X}_{LA} = \frac{K_{SA}}{L_A}X_{SA} - \frac{1}{L_A}F_{LA}, \quad (18)$$

$$\dot{X}_{SA} = \dot{X}_L - \dot{X}_{LA} \quad (19)$$

where A denotes the parameters of the third mass. The total external force on the load side F_{LA} without the vibration effect

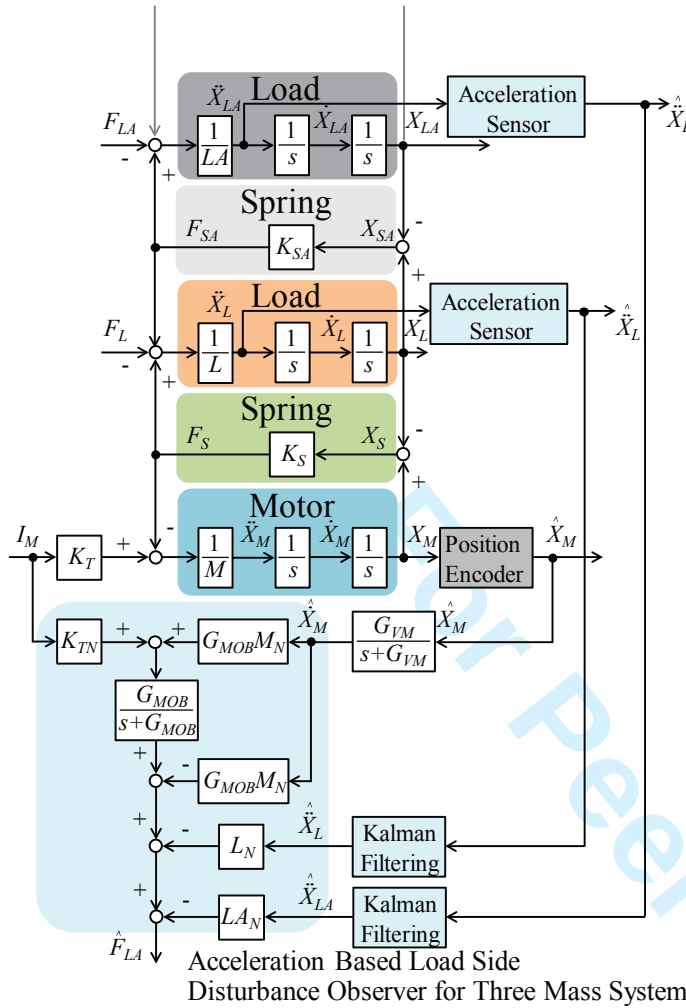


Fig. 7. Schematic diagram of acceleration load side disturbance observer for three-mass system.

can be estimated as

$$\begin{aligned}
 F_{LA} &= K_{TN}I_M - M_N\ddot{X}_M - L_N\ddot{X}_L - L_{AN}\ddot{X}_{LA} \quad (20) \\
 \hat{F}_{LA} &= \left(\frac{G_{MOB}}{s + G_{MOB}} \right) \left(K_{TN}I_M + G_{MOB}M_N\dot{X}_M \right) \\
 &\quad - G_{MOB}M_N\dot{X}_M - L_N\dot{X}_L - L_{AN}\dot{X}_{LA} \quad (21)
 \end{aligned}$$

As shown in Fig. 6 and 7, the Kalman-filter is applied to compensate the unwanted white Gaussian noise of the acceleration signal. The process of the Kalman-filter consisting of the operation in two phases: prediction and update. The formulation of the Kalman filter equation is based on state space formulation. A discrete sensor dynamics model can be formulated in the state space form as

$$\mathbf{x}_{(k+1)} = \mathbf{A}_{(k)}\mathbf{x}_{(k)} + \mathbf{B}_{(k)}\mathbf{u}_{(k)} + \mathbf{w}_{(k)} \quad (22)$$

$$\mathbf{z}_{(k)} = \mathbf{C}_{(k)}\mathbf{x}_{(k)} + \mathbf{v}_{(k)} \quad (23)$$

where k represents the sampling instant, $\mathbf{x}_{(k)} \in \mathbb{R}^n$ is the vector of states, $\mathbf{u}_{(k)} \in \mathbb{R}^m$ is the vector of input variables, $\mathbf{A}_{(k)} \in \mathbb{R}^{n \times n}$ and $\mathbf{B}_{(k)} \in \mathbb{R}^{n \times m}$ are system matrices,

$\mathbf{C}_{(k)} \in \mathbb{R}^{s \times n}$ is the measurement matrix, $\mathbf{z}_{(k)} \in \mathbb{R}^s$ is the vector of measured variables, $\mathbf{w}_{(k)}$ is the process noise and $\mathbf{v}_{(k)}$ represents the measurement which is corrupted by white Gaussian noise.

It is assumed that the covariance matrix of the process noise $\mathbf{Q}$, the covariance matrices of the measurement noise $\mathbf{R}$ and the cross-covariance matrix are as given below:

$$\mathbf{Q} = E\{\mathbf{w}\mathbf{w}^T\} > 0 \quad (24)$$

$$\mathbf{R} = E\{\mathbf{v}\mathbf{v}^T\} \geq 0 \quad (25)$$

$$E\{\mathbf{w}\mathbf{v}^T\} = 0 \quad (26)$$

The Kalman filter bandwidth and its susceptibility to measurement noise depends on its covariance matrix of process noise $\mathbf{Q}$ and the covariance matrix of measurement noise $\mathbf{R}$. These values are used to tune the accuracy and response of the observer, and the matrices $\mathbf{Q}$ and $\mathbf{R}$ can be determined by using the simulations for the testing of the measurement sensors. A compromise between the performance of observer and the compensation of acceleration signal noise can be found.

The error covariance matrices $\mathbf{P}$ is the variance of the difference between the state and the measurements. The predicted equation which projects the current state estimate ahead in time are given by

$$\mathbf{x}_{(k|k-1)} = \mathbf{A}_{(k-1)}\mathbf{x}_{(k-1|k-1)} + \mathbf{B}_{(k-1)}\mathbf{u}_{(k-1)} \quad (27)$$

$$\mathbf{P}_{(k|k-1)} = \mathbf{A}_{(k-1)}\mathbf{P}_{(k-1|k-1)}\mathbf{A}_{(k-1)}^T + \mathbf{Q}_{(k-1)} \quad (28)$$

The Kalman filter gain matrix $\mathbf{M}$, that is based on the total uncertainty measurement of matrix $\mathbf{S}$ is computed by using the following equation

$$\mathbf{S}_{(k)} = \mathbf{C}_{(k)}\mathbf{P}_{(k|k-1)}\mathbf{C}_{(k)}^T + \mathbf{R}_{(k)} \quad (29)$$

$$\mathbf{M}_{(k)} = \mathbf{P}_{(k|k-1)}\mathbf{C}_{(k)}^T\mathbf{S}_{(k)}^{-1} \quad (30)$$

The estimated state vector and the error matrix are updated by an actual measurement $\mathbf{z}_{(k)}$ of motion sensor at every sampling instant as follows

$$\mathbf{x}_{(k|k)} = \mathbf{x}_{(k|k-1)} + \mathbf{M}_{(k)}(\mathbf{z}_{(k)} - \mathbf{C}_{(k)}\mathbf{x}_{(k|k-1)}) \quad (31)$$

$$\mathbf{P}_{(k|k)} = \mathbf{P}_{(k|k-1)} - \mathbf{M}_{(k)}\mathbf{S}_{(k)}\mathbf{M}_{(k)}^T \quad (32)$$

IV. CONTROLLER DESIGN OF FLEXIBLE ROBOT SYSTEM

A. Resonance Ratio Control Based on CDM for Two-Mass System

A new effective control method, the resonance ratio control [12]–[14], has been introduced by Yuki et al. as a new way to guarantee the robustness and suppress the oscillation during task executions for a torsional vibration in the position control system [13]. Briefly, this approach relies on the possibility to change the virtual inertia moment in the motor side by feeding back the estimated reaction torque to the motor in an acceleration dimension. This means that the resonance frequency and the resonance ratio of the system can be changed to an arbitrarily value. Also, in [12], the resonance control is used in order to achieve the excellent performance that compensates vibration for high-bandwidth force servoing. Due to the compensation of disturbance observer on the motor side,

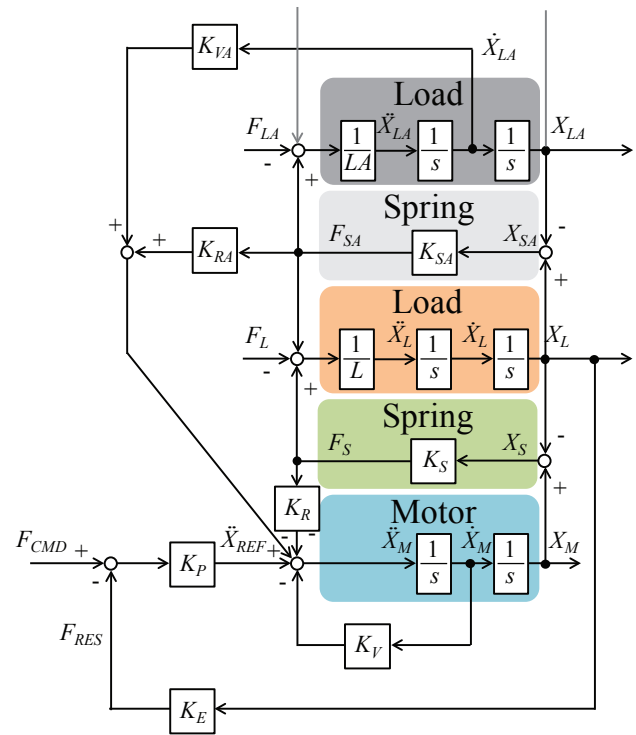


Fig. 9. The simplified block diagram of the resonance ratio control for three mass system.

From Fig. 6, the transfer functions from acceleration reference $\ddot{X}_{ref}$ to motor position $\hat{X}_m$ and motor position $\hat{X}_m$ to load position $\hat{X}_l$ can be calculated as follows,

$$a_0 = K_P K_E \omega_{AR}^2 \quad (38)$$

$$a_1 = K_V \omega_{AR}^2 \quad (39)$$

$$a_2 = \omega_R^2 \quad (40)$$

$$a_3 = K_V \quad (41)$$

$$a_4 = 1.0 \quad (42)$$

are found as,

$$\tau = \frac{a_1}{a_0} = \frac{K_V}{K_P K_E} \quad (43)$$

$$\gamma_1 = \frac{a_1^2}{a_0 a_2} = \frac{K_V^2 \omega_{AR}^2}{K_P K_{EW}^2 R} = 2.5 \quad (44)$$

$$\gamma_2 = \frac{a_2^2}{a_1 a_3} = \frac{\omega_R^4}{K_V^2 \omega_{AR}^2} = 2.0 \quad (45)$$

$$\gamma_3 = \frac{a_3^2}{a_2 a_4} = \frac{K_V^2}{\omega_R^2} = 2.0 \quad (46)$$

The standard stability indices γ_i for the Manabe form are chosen as $\gamma_1=2.5$, $\gamma_2=2.0$, and $\gamma_3=2.0$.

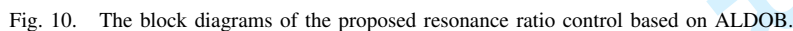
Thus, the controller parameters calculated by the design of CDM are given as follow,

$$K_V = \sqrt{2}\omega_R \quad (47)$$

$$K_P = \frac{4\omega_{AR}^2}{5K_E} \quad (48)$$

$$K = \frac{\omega_R}{\omega_{AR}} = 2.0 \quad (49)$$

$$K_R = \frac{3}{L} \quad (50)$$



can be defined as the following calculation:

$$\omega_{AR1}^2 \omega_{AR2}^2 = \frac{K_S K_{SA}}{L L_A} \quad (53)$$

A similar control architecture can be implemented in the multi-mass system. The block diagram representation of a resonance ration control for three mass system is shown in Fig. 9. If the acceleration signals are measured by sensors, the value of external torques or forces at the end-effector side can be determined by the ALDOB. Based on this principle, the external force from the load-side could be determined and compensated with a simple multiplication of the reaction force gain K_{RA} to the motor side. From the block diagram in Fig. 9, the transfer function of the three mass system from the force command F_{CMD} to the motor displacement X_M can be expressed as

where ω_{R1} and ω_{AR1} are the first resonance and anti-resonance frequency, and ω_{R2} and ω_{AR2} are the second resonance and anti-resonance frequency. The value of the ω_{AR1} and ω_{AR2}

$$\frac{F_{RES}}{F_{CMD}} = \frac{K_P K_E \omega_{AR1}^2 \omega_{AR2}^2}{a_6 s^6 + a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0} \quad (54)$$

The coefficients of characteristic polynomial a_i are found as,

$$a_6 = 1 \quad (61)$$

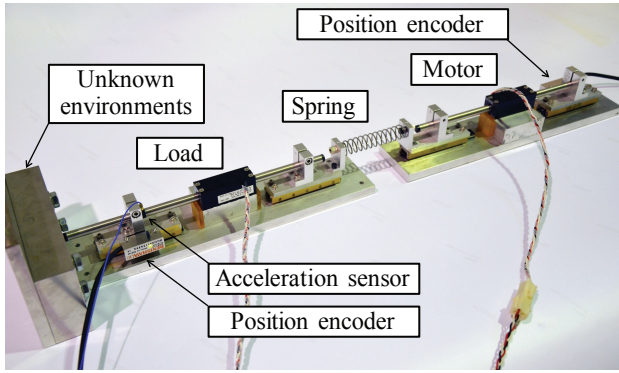


Fig. 11. Experimental setup of flexible robot system.

The standard stability indices γ_i for the Manabe form are chosen as $\gamma_1=2.5$, $\gamma_2=2.0$, $\gamma_3=2.0$, $\gamma_4=2.0$ and $\gamma_5=2.0$.

$$\tau = \frac{a_1}{a_0} = \frac{K_V + K_{VA}}{K_P K_E} \quad (62)$$

$$\gamma_1 = \frac{a_1^2}{a_0 a_2} = \frac{(K_V + K_{VA})^2}{K_P K_E (1 + (L + L_A) K_R + L_A K_{RA})} = 2.5 \quad (63)$$

$$\gamma_2 = \frac{a_2^2}{a_1 a_3} = \frac{\omega_{AR1}^2 \omega_{AR2}^2 (1 + (L + L_A) K_R + L_A K_{RA})^2}{K_V (K_V + K_{VA}) (\omega_{AR1}^2 + \omega_{AR2}^2)} = 2.0 \quad (64)$$

$$\gamma_3 = \frac{a_3^2}{a_2 a_4} = \frac{K_V^2 (\omega_{AR1}^2 + \omega_{AR2}^2)}{\omega_{AR1}^2 \omega_{AR2}^2 (1 + (L + L_A) K_R + L_A K_{RA})} \times \frac{1}{(\omega_{AR1}^2 + \omega_{AR2}^2 + K_S K_R)} = 2.0 \quad (65)$$

$$\gamma_4 = \frac{a_4^2}{a_3 a_5} = \frac{(\omega_{AR1}^2 + \omega_{AR2}^2 + K_S K_R)^2}{K_S K_R (\omega_{AR1}^2 + \omega_{AR2}^2)} = 2.0 \quad (66)$$

$$\gamma_5 = \frac{a_5^2}{a_4 a_6} = \frac{K_V^2}{\omega_{AR1}^2 + \omega_{AR2}^2 + K_S K_R} = 2.0 \quad (67)$$

CDM are given as follow,

$$K_V = \sqrt{8(\omega_{AR1}^2 + \omega_{AR2}^2)} \quad (68)$$

$$K_{VA} = \frac{\sqrt{8(\omega_{AR1}^2 + \omega_{AR2}^2)}((\omega_{AR1}^2 + \omega_{AR2}^2)^2 - 16\omega_{AR1}^2 \omega_{AR2}^2)}{16\omega_{AR1}^2 \omega_{AR2}^2} \quad (69)$$

$$K_R = \frac{3(\omega_{AR1}^2 + \omega_{AR2}^2)}{K_S} \quad (70)$$

$$K_{RA} = \frac{K_S(\omega_{AR1}^2 + \omega_{AR2}^2) - \omega_{AR1}^2 \omega_{AR2}^2 (K_S + 3(L + L_A))}{K_S(L + L_A)\omega_{AR1}^2 \omega_{AR2}^2} \quad (71)$$

$$K_P = \frac{LK_S A^2 \sqrt{8A}}{40K_E(L_A K_S(A^2 - B) + LB(K_S + 3(LA - L_A)))} \quad (72)$$

where

$$A = \omega_{AR1}^2 + \omega_{AR2}^2, B = \omega_{AR1}^2 \omega_{AR2}^2 \quad (73)$$

C. Feedforward load disturbance compensation

1) *Feedforward load disturbance compensation for two mass system:* The block diagram of the proposed control structure is shown in Fig. 10. The load disturbance compensation is introduced to compute and feedback the estimated load disturbance force through the inverse system of the motor side. The inverse system can be represented by the transfer function from F_{cmd} to F_{res} as shown in (20) and from F_{dl} to F_{res} as follows,

$$\frac{F_{RES}}{F_L} = \frac{\frac{1}{L} K_E (s^2 + K_V s + K_R K_S)}{s^4 + K_V s^3 + \omega_R^2 s^2 + K_V \omega_{AR}^2 s + K_P K_E \omega_{AR}^2} \quad (74)$$

Then, the inverse system can be calculated by the following equation:

$$\frac{F_{CMD}}{F_L} = \frac{s^2 + K_V s + K_R K_S}{K_P K_S} \quad (75)$$

2) *Feedforward load disturbance compensation for three mass system:* Using the same relationship as before, the transfer function relating force response F_{RES} , to the external force at the load side F_{LA} , for the three mass system is

$$\frac{F_{RES}}{F_{LA}} = \frac{K_E (b_4 s^4 + b_3 s^3 + b_2 s^2 + b_1 s + b_0)}{a_6 s^6 + a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0} \quad (76)$$

where

$$b_0 = (K_R + K_{RA}) K_S K_{SA}, b_1 = (K_S + K_{SA}) K_V \\ b_2 = K_R K_S L + K_S + K_{SA}, b_3 = K_V L, b_4 = L$$

Then, the feedforward load disturbance compensation for three mass system can be expressed as

$$\frac{F_{CMD}}{F_L} = \frac{b_4 s^4 + b_3 s^3 + b_2 s^2 + b_1 s + b_0}{K_P K_S K_{SA}} \quad (77)$$

For the flexible robot system having a multi mass, the proposed method can be applied and designed the controller and observer by calculating the transfer function of the multi mass system.

Thus, the controller parameters calculated by the design of

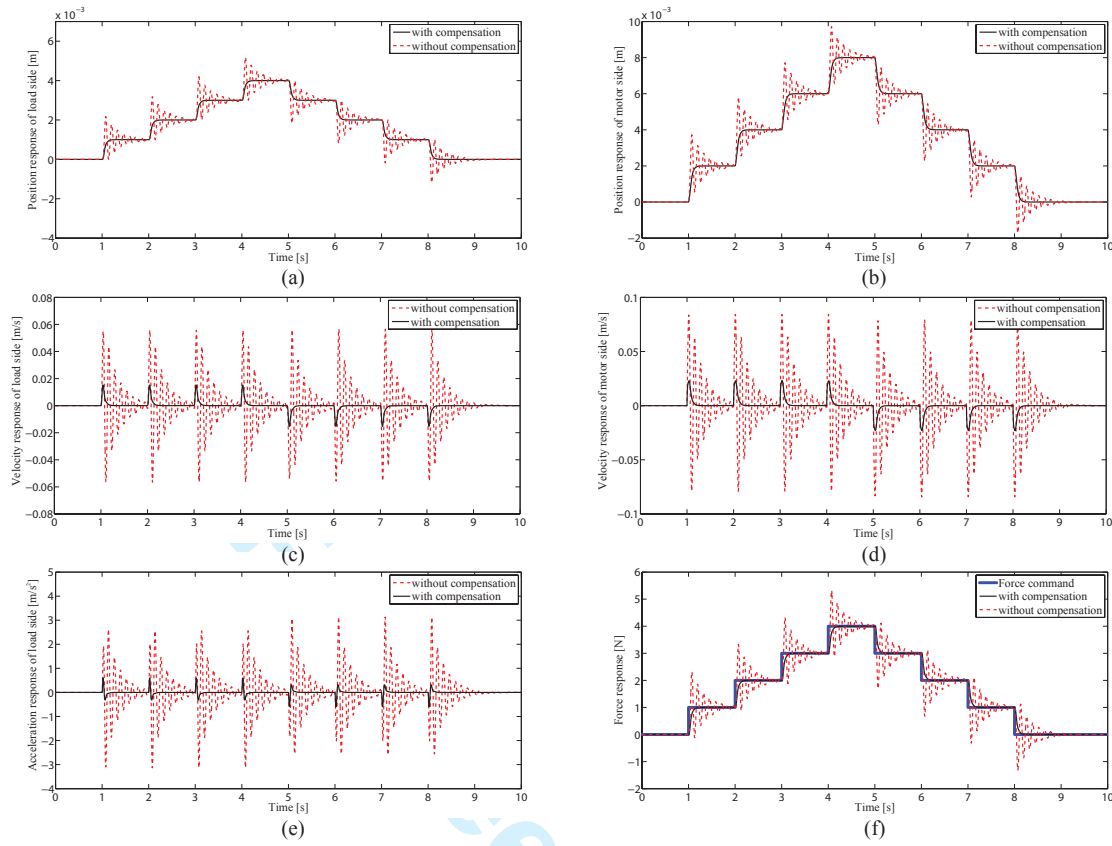


Fig. 12. Simulation results of two mass system.

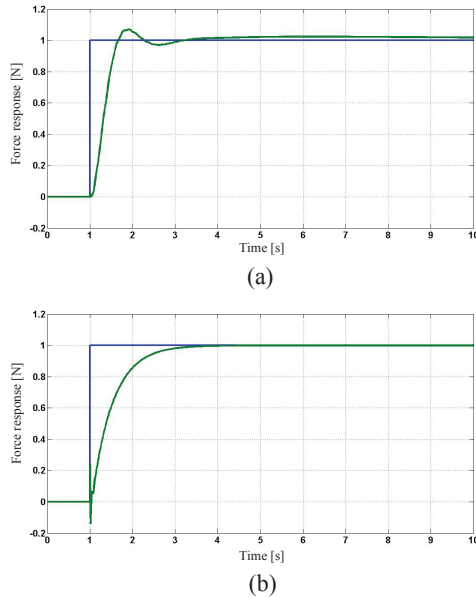


Fig. 13. Simulation results of three mass system.

V. SIMULATION RESULTS

In order to show the validity and usefulness, numerical simulations are given to confirm of the proposed controller and

observer design. Simulation was implemented using MATLAB software. First, simulation was conducted without the reactive force feedback, and the position, velocity, acceleration, and the contacted force responses were collected as shown in Fig. 12. From the results, the force command input is a stepwise function. It is seen from Fig. 12 (f) that without reaction force compensation feedback give a poor response with a very large vibration. On the other hand, the vibration are well compensated in the case of the resonance ratio control. It is clear from these results that the resonance ratio control based on CDM design approach gives a good response with no overshoot and short settling time compared to the conventional PID controller design.

Extending from our proposed method , the resonance ratio control based on three mass system was tested. The input step function is used as the force command. The results obtained from the proposed approach is compared with the results obtained from the conventional PID control with the disturbance force compensation loop. From Fig. 13 (b), it is also confirmed that the resonance ratio control can compensate for vibration effect of the contacted force response completely.

VI. EXPERIMENTAL RESULTS

This section describes experimental implementation of resonance ratio control using ALDOB in real conditions, and the contacted force response, the speed and position of motor

and load were being investigated. The control algorithm was implemented in a PC using RT-Linux with a sampling time of 100 μ s. The specifications of the linear motor system, sensor devices, and the parameters used in the experiment are shown in Table I. To verify the proposed observer and controller design of the flexible robot system, an acceleration sensor and linear optical encoder were implemented in the experimental feedback control system. In this paper, the experimental setup consists of two different types of motion sensors.

A. 1) Optical Linear Encoder:

A noncontact optical linear encoder (RGH24 series; Renishaw) with high resolution grade of 0.1 μ m is used to read the scale in order to convert the encoded position into a digital square-wave signal. The scale substrate for measuring position is a thin flexible steel strip, which is gold plated to give high reflectivity and corrosion resistance. It has been designed to make relevant the unwanted effects of electromagnetic interference.

B. 2) Acceleration Sensor:

A mounting wax is used to mount piezoelectric acceleration sensors (NP-3211; Ono Sokki Technology, Inc.) on the master and slave robots, and these sensors are applied to convert mechanical vibrations into analog signals. The outer dimension of sensor has a dimension of 6.4 $\times$ 11.4 $\times$ 3.6 mm and the weight of sensor is 5 g. It offers a sensitivity of 1.02 mV with 1 m/s². The structure of the sensor is a shear type, which is fixed in place between a post and inertial mass. The frequency response range is provided from 1 Hz to 10 kHz. In the actual application, the use of an acceleration sensor has some drawbacks due to high noise sensitivity.

The acceleration was mounted on a linear motor at the load side, which has an optical encoder installed in order to observe vibration effect at the motor side and load side. The parameter in the controller were tuned to match the controller design in the identify transfer function of flexible robot system. All of the identified parameters was used to calculate the controller gain. The input stepwise is used as the force command. The control structure of resonance ratio control with a two-mass system as shown in Fig. 10 was investigated.

In the first experiment, a sponge was prepared as a sample environment for the test. An aluminum block was set at the end-effector in the second experiment. The aluminum block is usually stiffer than the sponge. It was embedded close to the end-effector of the robot. The responses of motor side and load side are shown in Figures 14 (a), (b) and 15 (a), (b) and the responses of the contacted force estimation by using ALDOB and LDOB are shown in Fig. 14 (f) and 15 (f). Without the vibration compensation, it is found that the responses of position, velocity at the motor side and load side are oscillated. The influence of the reaction force feedback can be observed to significantly reduced the effective vibration by using the resonance ratio control. The improvement in the position and velocity responses at the motor side and load side are illustrated

TABLE I
PARAMETERS USED IN EXPERIMENTAL SETUP

Controller parameters	Symbol	Value	Units
Mass of motor	M	0.245	kg
Force constant coefficient	K_t	3.333	N/A
Mass of load	L	0.245	kg
Spring coefficient	K_{SN}	1100	N/m
Force gain	K_P	3.59	
Velocity gain	K_V	189.52	
Reaction force gain	K_R	12.24	
Resonance ratio gain	K	2	
Cut-off freq. of vel.	G_{VE}	1000	rad/s
Cut-off freq. of DOB.	G_{DIS}	1000	rad/s
Cut-off freq. of LDOB.	G_{LOB}	800	rad/s
Cut-off freq. of MEDOB.	G_{MOB}	800	rad/s
Specification of sensors	Symbol	Value	Units
Optical encoder		0.1	μ m
Acceleration sensor	Symbol	Value	Units
Bandwidth of acceleration sensor		1~10K	Hz
Weight of the acceleration sensor		5.0	g

During the test, the contacted force estimation using ALDOB were checked to confirm they matched the contacted force estimation using MEDOB during experiments. By using LDOB, the mismatched value of the spring coefficient K_S caused incorrect estimation in the contacted force response. If the spring coefficient is accurately identify, the force estimation can be improved the accuracy of the force estimation.

Figure 14 (f) and 15 (f) show the force response without and with compensator. The controller without the reaction force feedback compensation was chosen to illustrate the worst-case vibration. Based on the force estimation recorded during the test, the system force of the proposed method followed the reference command with only a small tracking error. By using the proposed resonance ratio control with ALDOB, it is observed that the oscillation in the contacted force response were small. The spring vibrations were significantly reduced in the contacted force response. It was shown that the resonance ratio control can suppress the oscillation more effectively than a conventional PID control.

VII. CONCLUSION

In this paper, we described how acceleration sensor was integrated with ALDOB to estimate and control the contacted force. Since acceleration sensors can be implemented in a small area on the load side, it is considered to be suitable for the real applications. The proposed ALDOB observer can be utilized with resonance ratio control to suppress high-frequency vibrations of spring. Since the optimal parameters is designed by using coefficient diagram method, the resonance ratio control can ensure good robustness of the force control. We performed this analysis for two types of systems, the two mass system and three mass system, which are representative of many physical systems. Moreover, this proposed approach could also be applied for other multi mass system. The obtained simulation and experimental results confirmed the efficiency of the proposed resonance ratio control with ALDOB for the robust force control system without use of force sensors.

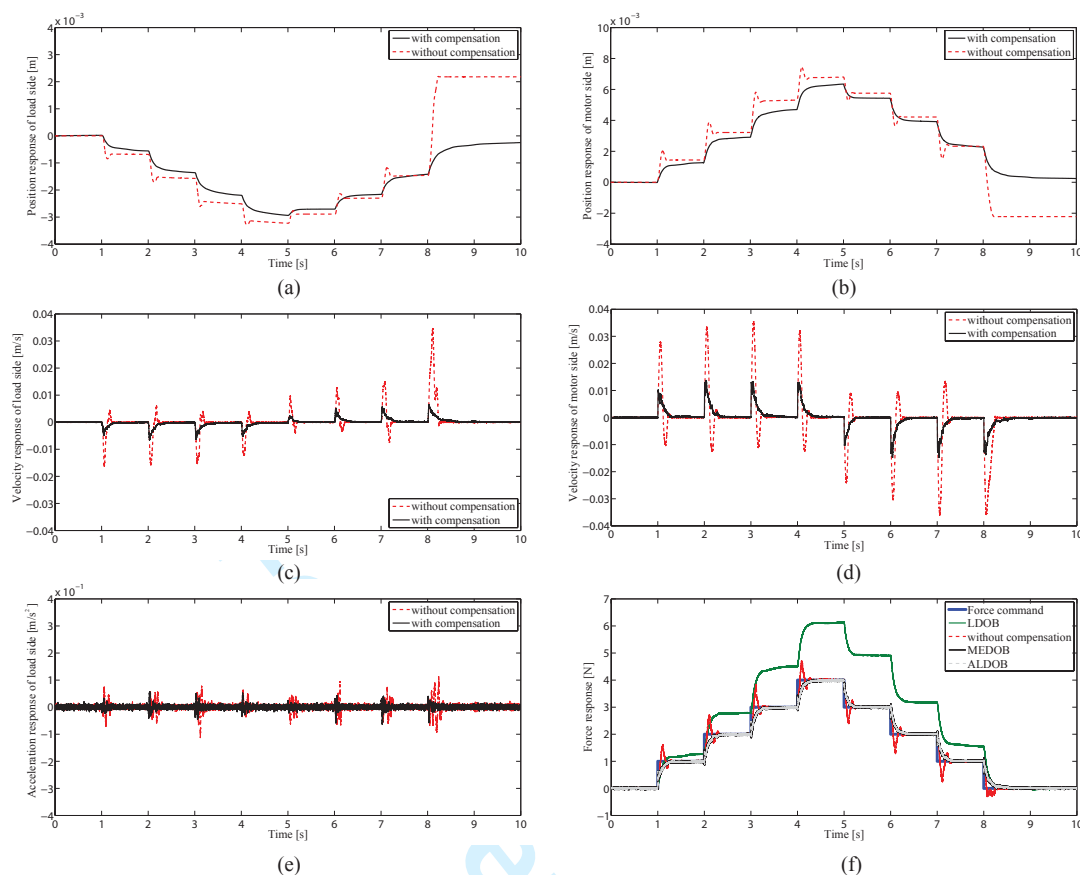


Fig. 14. Experimental results of sensorless force control system with sponge.

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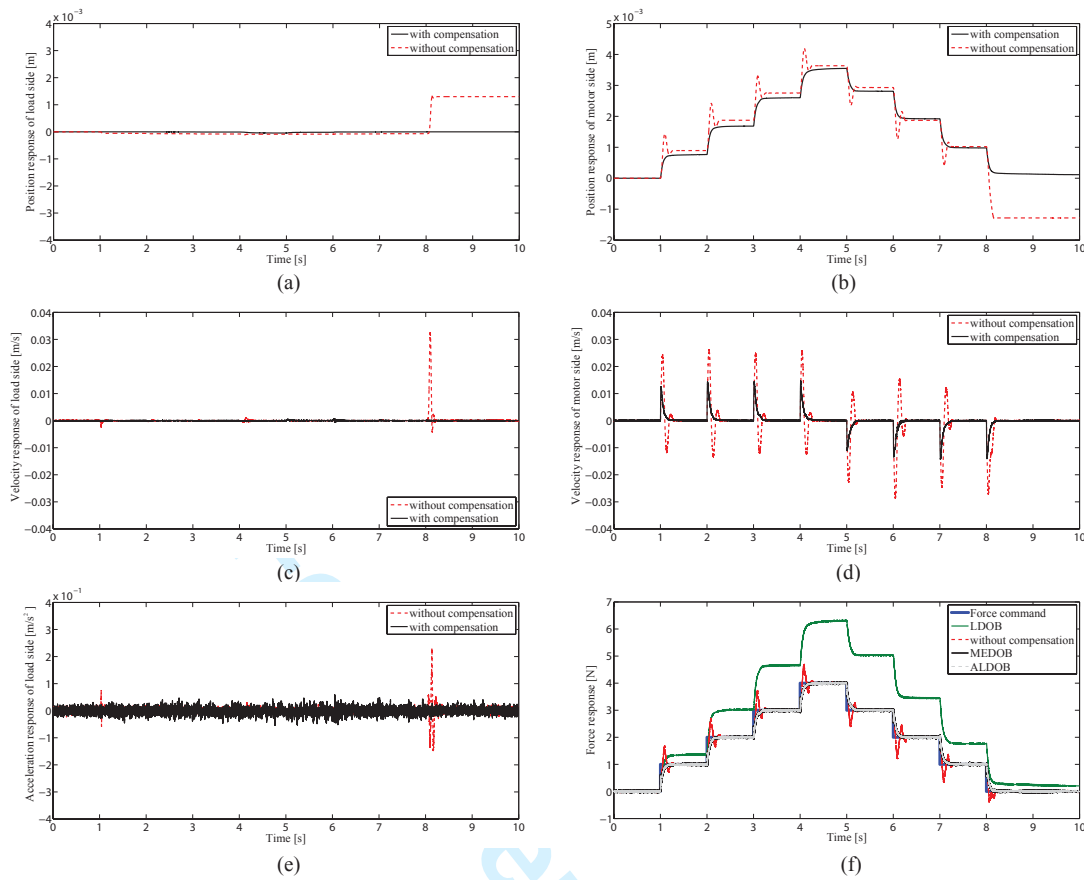


Fig. 15. Experimental results of sensorless force control system with aluminum block.

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Micro-macro Bilateral Control in Delta Robot

Sorawit Stapornchaisit¹, Chowarit Mitsantisuk²

Abstract – This paper present new method to perform micro-macro bilateral control system in robot with non-linear kinematic property between task space and controllable space, the example is parallel Delta Robot which is selected due to better interact with human, light weight, fast movement and 3-dimension movement. The conventional micro-macro bilateral control using Hadamard matrix cannot achieve micro-macro bilateral properties of Delta Robot due to dimension shifting which lead to different in both position and force space and loss of sensibility in haptic interface properties. The actual robot is built with design properties of low friction that reduce the complexity of dynamic model of Delta Robot. The controllable space or joint space is convert to task space using mathematic model. Moreover, the force applied on task space is estimated using sensorless force control system or disturbance observer and convert to task space by Andre Olsson's dynamic model of Delta Robot.

Keywords: Parallel robots, Force control, Haptic interfaces, Robot control, Robot kinematics, Robot sensing systems

I. Introduction

Recently, industry have various application relate to robot which reduce the work force requirement, more accuracy and better reliability than human. The industry robot are focus on the position and velocity of the robot to increase reliability and reduce time consume. However, such control system cannot interact with human due to limitation and error of human muscular motor system. Therefore new control method focusing on the interaction with human is invented and called motion control.

In order to control the robot with caution to human interaction, the human movement method is considered as force control system which mean the robot need combination of both position and force control and one of the popular method recently is bilateral control. Bilateral control using idea of control position and one robot and force on another robot which result in haptic sensation on both side [1]-[5]. Moreover, the method to increase sensibility and accuracy of robot is implement using the advantage of scaling position and force between master and slave robot called micro-macro bilateral control [6]. Conventionally, the micro-macro bilateral control is applied on joint space (motor) of force controllable robot and not practical in Delta Robot for human interaction because it's cause unbalance inertial in different axis movement. Therefore, new method that concern on the control Delta Robot in task space (travelling plate) in both position and force term is required to achieve micro-macro bilateral control and also prove the concept of controllable desired space that provide by Hadamard matrix

Delta Robot is a kind of parallel manipulators that have been developed since 1980 and shown enormous progress to handle human robot interaction problem such as 3 dimension movements and force, small moving part, higher interaction speed, better compatibility with human than conventional serial robot [7]-[8] and capable of accelerating up to 100 times of gravity force which is popular in industrial [9]. The unique properties of Delta Robot is the travelling plate or end effector that connect with base plate using three legs and universal joint. The position of travelling plate is related to position of base plate and determined by angular position of each motor which lead to complicate kinematic, meanwhile, the force applied on travelling plate or any parallel link of Delta Robot will be convert to the movement of motor and detectable by disturbance observer [10]. Moreover, Delta Robot have better force transfer between travelling plate (task space) and motor (joint space) due to higher stiffness of system in 3 dimensional space because of rotating coordinate closed chain system [11]. Furthermore, Delta Robot offer higher rigidity and stiffness perpendicular to the travelling plate which reduce noise cause by human hand as proposed to cure Parkinson's disease that need very high rigid human hand to insert biopsy needle into brain called Parallel Kinematic Machine (PKM) [12]. However, Delta Robot have relatively smaller workspace compare to serial robot, design difficulties and problem of finding closed from expressions for direct kinematics. The widely known example is the one designed by Clavel [13] with closed-form solutions that enable accurate design and efficient control method.

The mathematic represent the relation of force between motor and travelling plate called dynamic model

is applied according to Andre Olsson's method. Inverse dynamic model is calculated by Newton-Euler method [14] with d'Alembert virtual work principle is achieved by mean of some Jacobian matrix. The friction force is minimal by mechanism design and neglected to simplify the dynamic system of Delta Robot.

In order to apply force control to the system, force sensor usually be implemented at the end of travelling or end effector. However, force sensor shown various disadvantages such as high cost, limitations imposed on bandwidth and resonant structural. Therefore, new method to leave force sensor is implement and the force applied on travelling plate is sensed by sensorless force control technology with feedback disturbance observer to improve the robustness of motor, various previous practical force control system have confirmed that the disturbance observer can estimate the external force instead of the real force sensor [15] – [20].

This paper is organized as follows. The model and mathematic calculation related to the proposed method such as, converting between controllable space or joint space and task space, disturbance observer and partial gravity compensation is introduced in Section II. The proposed method is explained in Section III and experimental setup and parameter is shown in Section IV. The result and discussion are present in Section V and followed by the conclusions in Section VI.

II. Delta Robot Modelling

Delta Robot is a parallel robot with three kinematic chains connect between base plate and travelling plate. The movement of Delta Robot is defined by movement of parallelograms of upper-arms, fore-arms and bidirectional joint or ball joint, the component of Delta Robot is shown in Fig. 1.

The reference frames is separated into two frames as shown in Fig. 2 and Fig. 3, Inertial frames of base plate (O_b, X_b, Y_b, Z_b) and inertial frames of travelling plate (O_t, X_t, Y_t, Z_t) have origin point at the center of base plate and travelling plate, respectively. The direction of X-axis is $\pi/6$ clockwise (CW) from first motor and $\pi/2$ counterclockwise (CCW) from third motor. The reference frame of each motor from inertial frames of base plate is represented by α_i associated with each upper arm is defined as $\pi/6, 5\pi/6$ and $3\pi/2$ for $i = 1, 2, 3$.

The length of upper-arm is represented by L_1 attached at the edge of base plate with radius of R . Likewise, The length of fore-arm is represented by L_2 attached to the edge of travelling plate with the radius of r . Secondary angle θ_{i2} and third angle θ_{i3} of fore arm are correspond with the position of ball joint and travelling plate or the coordination between three motors. Using all variable definitions in this section to convert both position and force between joint space and task space. The method to convert position called kinematic and method to convert force using dynamic model properties of Delta Robot.

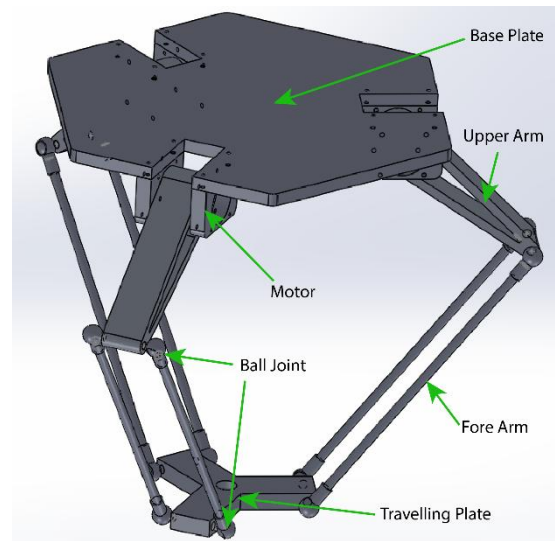


Fig. 1. Structure and component of Delta Robot

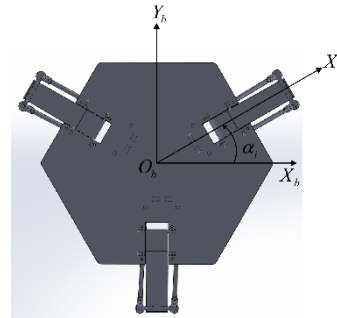


Fig. 2. Top view of a Delta Robot [21]

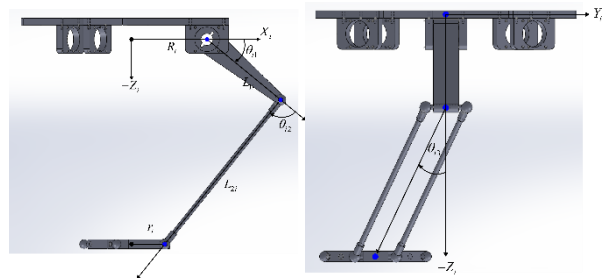


Fig. 3. Side and front view of Delta Robot [21]

II.1. Forward Kinematic

The position of travelling plate relative to position of base plate is result of angular position of three motors, the idea is to find the intersection of three sphere equations with radius of fore-arm that have origin position determinate by angular position of motors and length of upper-arm as shown in Fig. 4. The origin position of three sphere is expressed by (1) for $i = 1, 2, 3$.

$$\begin{aligned} X_i &= (R + L_1 \cos \theta_{i1} - r) \cos \alpha_i \\ Y_i &= (R + L_1 \cos \theta_{i1} - r) \sin \alpha_i \\ Z_i &= -L_1 \sin \theta_{i1} \end{aligned} \quad (1)$$

Using three sphere equations of each motor to calculate the intersection which result in two answer as shown in (2), pick the one with lower Z-axis, the position of travelling plate (X_t, Y_t, Z_t) represented by

$$(X_t - X_i)^2 + (Y_t - Y_i)^2 + (Z_t - Z_i)^2 = L_2^2 \quad (2)$$

II.2. Inverse Kinematic

From forward kinematic, the position of travelling plate is calculated by corresponded angular position of motor, the inverse method applied easier calculation due to close loop chain properties of Delta Robot to find corresponded angular position of each motors that provide desired travelling plate position (X_b, Y_b, Z_b). For any travelling plate position given by [X_t, Y_t, Z_t], combine with only and only if the (3) is satisfied, the solution of angular position is express in (4).

$$4Z_{pi}^2 + 4R_1^2 - S_i^2 + Q_i^2 \left(1 - \frac{R_1^2}{L_1^2} \right) - Q_i \left(4R_1 + \frac{2R_1 S_i}{L_1} \right) \geq 0 \quad (3)$$

$$\tan\left(\frac{\theta_{i1}}{2}\right) = \frac{-2Z_{pi} \pm \sqrt{4Z_{pi}^2 + 4R_1^2 - S_i^2 + Q_i^2 \left(1 - \frac{R_1^2}{L_1^2} \right) - Q_i \left(4R_1 + \frac{2R_1 S_i}{L_1} \right)}}{-2R_1 - Q_i \left(\frac{R_1}{L_1} - 1 \right) - S_i} \quad (4)$$

where

$$R_1 = R - r, \quad Q_i = 2X_{ti} \cos \alpha_i + 2Y_{ti} \sin \alpha_i$$

$$S_i = \frac{1}{L_1} (-X_{ti}^2 - Y_{ti}^2 - Z_{ti}^2 + L_2^2 - L_1^2 - R_1^2)$$

for $i = 1, 2, 3$.

R_1 represent the sum distance between base plate and travelling plate, Q_i is reference frames of motor using dimension shifting method and S_i provide the two circle equation in proper form.

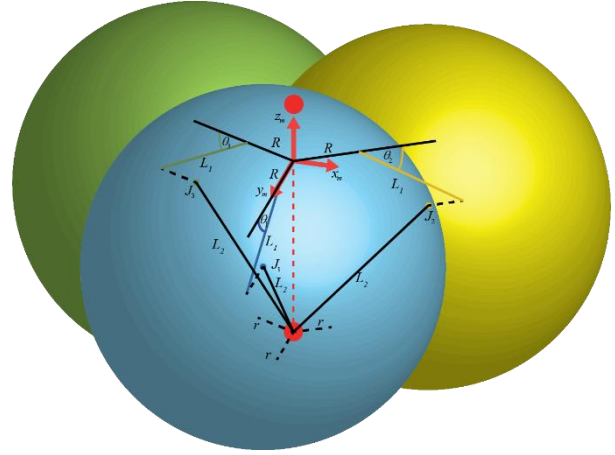


Fig. 4. Forward Kinematic for Delta Robot

II.3. Dynamic Model of Delta Robot

Dynamic model of Delta Robot has complexity due to the interference movement of fore-arm, therefore the dynamic model for Delta Robot is calculated with Newton-Euler method with simplifying hypotheses [13] as following.

- The rotational inertias of the forearms are neglected.
- The masses of Delta Robot is separate at fore-arm into top-links and bottom-links given by inertial of $I = 1/3mL^2$ show that the 1/3 of the forearms mass can combine with travelling plate and 2/3 of forearms mass can combine with upper-arm when consider the inertia at the ball joint.
- External force applied on and only on the travelling plate of Delta Robot.
- The friction and elasticity is neglected.

The dynamic system of Delta Robot is achieved by applied complicate linear decoupled and non-linear coupled part as shown in Fig. 5, the linear decoupled part consist of K_r describes matrix of the gear reduction ratio, $\bar{A}$ is the diagonal matrix whose control elements representing the average inertia at each joint, F_m describes the friction coefficients of manipulator, A is the inertia matrix, C describes the accounting of the centrifugal and Coriolis forces and G contains the gravity forces acting on the manipulator.

d'Alembert's principle defined that the contribution of all the inertial forces must equal the contribution of all the non-inertial forces. More accurately, the force applied on system must equal the force generated by moving part of system. Therefore, the force of motors and force of gravity is force applied on the system or non-inertial forces and movement of top-links and bottom-links is inertial forces as shown in (5). Assume that the operator force or force applied on travelling is converted to the movement of bottom-links.

$$\tau_M + \tau_{Guf} + \tau_{Gftp} = I_u \ddot{\theta} + \tau_i \quad (5)$$

where τ_M is torque generated by motor. τ_{Guf} and τ_{Gftp} are torque applied by gravity on top-links and bottom-links, respectively. I_u is sum of inertial applied on motor and τ_i is torque from bottom-links movement express by (6).

$$F_{ext} = (J^T)^{-1} \tau_i \quad (6)$$

where F_{ext} is disturbance force applied on travelling plate and Jacobian matrix (J) [22] is a mapping from motor angular velocity to travelling-plate linear velocity.

Simplifying hypotheses indicate that the inertial of motor attach with top-links and bottom-links represented by (7).

$$I_u = I_n k r^2 + I_{brake} k r^2 + I_A^2 \left(\frac{m_u}{3} + m_b + r m_f \right) \quad (7)$$

where I_n is motor inertial, I_{break} is inertial of break attached to the motor, m_u is mass of upper-arm, m_b is mass of ball joint or elbow, m_f is mass of fore-arm where $r = 2/3$ from simplifying hypotheses.

II.4. Disturbance Observer

In order to implement haptic system, the force sensor is applied to the tip or contact position between object and robot to sense external force and reproduce to the operator on master side. However, force sensor shown many disadvantage such as high cost, limitations on bandwidth and resonant structural. Therefore, disturbance observer (DOB) has been used in many application to estimate the external force using energy model of conventional motor model which increase the bandwidth of control system is proposed. Various previous research confirm that DOB implemented as feedforward control for a disturbance torque compensation loop can obtain stable force control system. The conventional motors model with disturbance observer is considered as shown in Fig. 6 and expressed by (8).

$$I_u \ddot{\theta}_m = K_t I_m - (\tau_f + D \dot{\theta}_m + \tau_{ext} + \Delta I_u \dot{\theta}_m + \Delta K_t I_m) \quad (8)$$

$$\tau_l = \tau_f + D \dot{\theta}_m + \tau_{ext}$$

$$\tau_{dis} = \tau_f + D \dot{\theta}_m + \tau_{ext} + \Delta M \dot{\theta}_m + \Delta K_t I_m \quad (9)$$

where θ_m , $\dot{\theta}_m$ and $\ddot{\theta}_m$ denote motor angular position, motor angular velocity and motor angular acceleration, respectively. K_t is torque coefficient of motor and I_m is motor current. The load torque τ_l is summation of friction torque τ_f , viscous friction $D \dot{\theta}_m$ and disturbance force on motor side τ_{dis} is expressed by (9)

Therefore, the relation between dynamic model of Delta Robot (5) and DOB (7) indicate that the external force on travelling or the movement due to external force

include the gravity force on travelling plate can be estimated as shown in (10).

$$I_u \ddot{\theta}_m = K_t I_m - (\tau_i - \tau_{Guf} - \tau_{Gftp}) \quad (10)$$

$$\tau_{dis} = (\tau_i - \tau_{Guf} - \tau_{Gftp})$$

According to dynamic model of Delta Robot and properties of disturbance observer, the complicate dynamic model of Delta Robot can achieve dynamic moment by install force feedback disturbance observer in each motor. Therefore, the dynamic system of Delta robot can be calculated by (5) and (7), the gravitational have influence on motor in the same time as disturbance force which is needed to be eliminated to acquire only the external force on travelling plate as shown in (11)

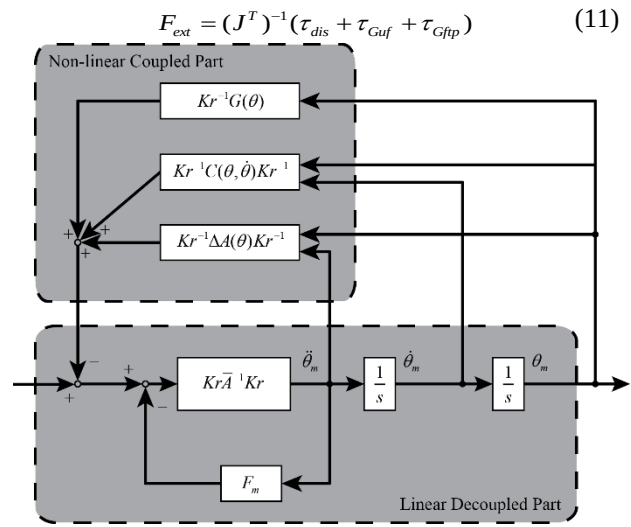


Fig. 5. Conventional dynamic system for delta robot [22]

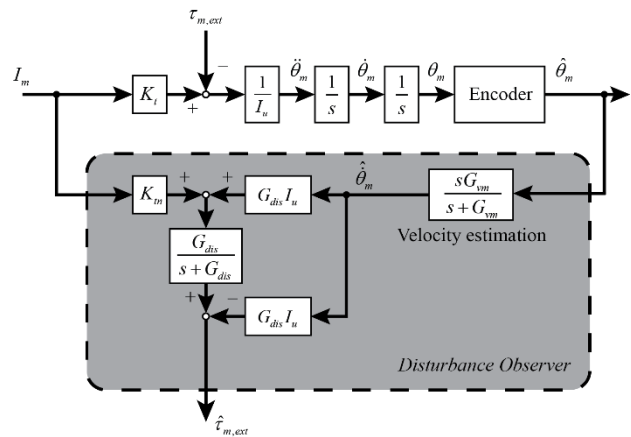


Fig. 6. Conventional motor model

II.5. Gravity Compensation

The dynamic model of Delta Robot is simplified by Newton-Euler method using three motors generate torque

to both simulate the reaction force and compensate for gravity force applied on the structure of Robot. This method can be done because the forces and moments of gravity force are transfer to upper-arm joint coordination. The gravity force is separated into two part of top-links and bottom-links. For bottom-link part, weight owing to the travelling plate, payload, and portion of three fore-arm links can be written as $W_{ftp} = m_{ftp}[0,0,-g]^T$ where m_{ftp} is 1/3 of the sum of three fore-arm masses ($m_f/3$), travelling-plate mass (m_t) and payload mass (m_p). Likewise, in top-links, weight from three upper arm and the portion of three fore-arms is $W_{uf} = m_{uf}[0,0,-g]^T$ where m_{uf} is sum of 2/3 of three fore-arm masses ($2m_f/3$), ball-joint mass (m_b) and upper-arm mass (m_u). Gravity torques resulted from top-link and bottom-link gravitational forces represented by (12).

$$\begin{aligned} \tau_{Guf} &= W_{uf} r_{Guf} [\cos \theta_1 \quad \cos \theta_2 \quad \cos \theta_3] \\ \tau_{Gftp} &= J^T W_{ftp} \end{aligned} \quad (12)$$

where r_{Guf} is defined as L_1 length weighted by ratio of top-link mass and bottom-link mass (13).

$$r_{Guf} = L_1 \frac{m_u/2 + m_b + 2m_f/3}{m_u + m_b + 2m_f/3} \quad (13)$$

However, the gravity force applied on top-links and bottom-links of Delta Robot are difficult to accurately calculate due to the measurement error of variable. Therefore, this method only applied to help reduce the gravity force load on operator which can be significantly large due to force scaling gains.

III. Micro-macro Bilateral Control

Recently, the technology to enhance human ability using robot has been given great success in various field such as medicine, industries and information. The robot with master-slave configuration controlled by bilateral

control has been proved in many research to achieve the haptic sensing of the environment using sensorless force control technology. In order to develop the technic further, the method to increase human perception and accuracy of bilateral control or haptic system called micro-macro bilateral control. Micro-macro bilateral control take advantage of data exchanges between two robot by amplified the data of slave robot with some value of scaling gains, the operator can increase or decrease the accuracy and sensibility of position and force, respectively.

Conventional micro-macro bilateral control using the data from encoder and DOB to control the position and force of each motor, such control method cannot compensate for non-linear properties of Delta Robot and result in distortion of both position and force response in task space of master and slave robot. Therefore, new method that concern on non-linear properties of system is required in order to achieve proper control system.

The control target of micro-macro bilateral control is minimize the different of displacement from origin of travelling plate between master ($X_{t,m}, Y_{t,m}, Z_{t,m}$) and scaled slave robot ($\beta X_{t,s}, \beta Y_{t,s}, \beta Z_{t,s}$), the origin position is set to the position of travelling plate where the angular position is zero or initial as shown in (14).

$$\begin{aligned} \hat{X}_{t,m} &= \beta \hat{X}_{t,s} \\ \hat{Y}_{t,m} &= \beta \hat{Y}_{t,s} \\ \hat{Z}_{t,m} &= \beta \hat{Z}_{t,s} \end{aligned} \quad (14)$$

where $X_{t,s}$, $Y_{t,s}$ and $Z_{t,s}$ denote displacement from origin in X-axis, Y-axis and Z-axis on travelling plate of master robot, $X_{t,m}$, $Y_{t,m}$ and $Z_{t,m}$ denote displacement from origin in X-axis, Y-axis and Z-axis on travelling plate of slave robot. β denote displacement scaling gains.

Likewise, the second control target is acquired the force response in travelling plate of master side ($F_{x,m}, F_{y,m}, F_{z,m}$) and travelling plate of slave side with scaling gains ($\alpha F_{x,s}, \alpha F_{y,s}, \alpha F_{z,s}$) following the third law

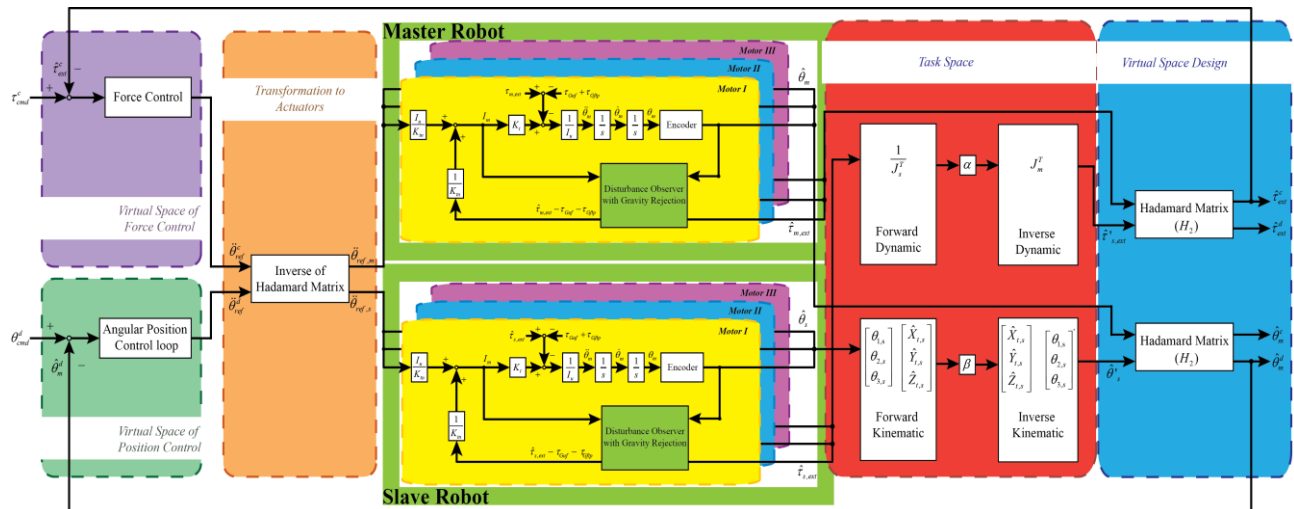


Fig. 7. Proposed Task Space Micro-macro Bilateral Control in Delta Robot for 3-Dimensional Tele-operated Manipulator Model

of Newton or Newton law of action and reaction as shown in (15).

$$\begin{aligned}\hat{F}_{x,m} + \alpha \hat{F}_{x,s} &= 0 \\ \hat{F}_{y,m} + \alpha \hat{F}_{y,s} &= 0 \\ \hat{F}_{z,m} + \alpha \hat{F}_{z,s} &= 0\end{aligned}\quad (15)$$

where $F_{x,m}$, $F_{y,m}$, $F_{z,m}$ denote external force applied on x-axis, y-axis and z-axis of travelling plate of master robot, respectively. $F_{x,s}$, $F_{y,s}$, $F_{z,s}$ denote external force applied on x-axis, y-axis and z-axis of travelling plate of slave robot. α denote force scaling gains.

The control of position and force in micro-macro bilateral control is separated into common mode and differential mode, respectively. The Hadamard matrix H_2 [23] is applied as shown in Fig. 7 to convert position θ_m , θ_s and torque $\tau_{m,ext}$, $\tau_{s,ext}$ of motor into virtual space model which consist of position dimension of common mode $\theta_{m,c}$ and differential mode $\theta_{m,d}$, external torque dimension of common mode $\tau_{ext,c}$ and differential mode $\tau_{ext,d}$. Both system are calculated by (16) and (17), respectively.

$$\begin{bmatrix} \theta_{m,c} \\ \theta_{m,d} \end{bmatrix} = \begin{bmatrix} 1 & f(J_m, J_s, \alpha) \\ 1 & -f(\theta, \beta) \end{bmatrix} \begin{bmatrix} \theta_m \\ \theta_s \end{bmatrix} = H_2 \begin{bmatrix} \theta_m \\ \theta_s \end{bmatrix} \quad (16)$$

$$\begin{bmatrix} \tau_{ext,c} \\ \tau_{ext,d} \end{bmatrix} = \begin{bmatrix} 1 & f(J_m, J_s, \alpha) \\ 1 & -f(\theta, \beta) \end{bmatrix} \begin{bmatrix} \tau_{m,ext} \\ \tau_{s,ext} \end{bmatrix} = H_2 \begin{bmatrix} \tau_{m,ext} \\ \tau_{s,ext} \end{bmatrix} \quad (17)$$

where $f(J_m, J_s)$ denote gain in joint space of torque which can be calculated by ratio of Jacobian matrix of slave and master robot as shown in (18). $f(\theta, \beta)$ denote gain in joint space of angular position which is non-linear due to non-linear kinematic of delta robot but can be calculated by ratio of virtual angular position of slave θ'_s divide by angular position of slave θ_s as shown in (19) [24].

$$f(J_m, J_s, \alpha) = \alpha J_m^T (J_s^T)^{-1} \quad (18)$$

$$f(\theta, \beta) = \frac{\hat{\theta}'_s}{\hat{\theta}_s} \quad (19)$$

The appropriate gain of position control is acquired by convert the angular position of slave robot to position in task space using forward kinematic of slave robot represented by function $(FK_s(\theta))$ as shown in (20), then reconvert into angular position using inverse kinematic of master robot represented by function $(IK_m(X_t, Y_t, Z_t))$ as shown in (21).

$$\begin{bmatrix} X_{t,s} & Y_{t,s} & Z_{t,s} \end{bmatrix}^T = FK_s(\hat{\theta}_s) \quad (20)$$

$$\hat{\theta}'_s = IK_m \left(\begin{bmatrix} \beta X_{t,s} & \beta Y_{t,s} & \beta Z_{t,s} \end{bmatrix}^T \right) \quad (21)$$

Finally, the control goal of micro-macro bilateral control's position (14) is confirm and realized by (22) and force (15) is confirm and realized by (23).

$$\begin{aligned}FK_m(\hat{\theta}_m) - \beta * FK_s(\hat{\theta}_s) &= 0 \\ \begin{bmatrix} X_{t,m} & Y_{t,m} & Z_{t,m} \end{bmatrix}^T &= \begin{bmatrix} \beta X_{t,s} & \beta Y_{t,s} & \beta Z_{t,s} \end{bmatrix}^T\end{aligned}\quad (22)$$

$$\begin{aligned}(J_m^T)^{-1} \tau_{m,ext} + \alpha (J_s^T)^{-1} \tau_{s,ext} &= 0 \\ \begin{bmatrix} F_{x,m} & F_{y,m} & F_{z,m} \end{bmatrix} + \begin{bmatrix} \alpha F_{x,s} & \alpha F_{y,s} & \alpha F_{z,s} \end{bmatrix} &= 0\end{aligned}\quad (23)$$

The control system is separate into two part according to control target, position control in differential mode is analyzed as the proportional-derivative controller. On the other hand, force control in common mode is separately analyzed as the proportional controller. The model space of each mode is designed and controlled in acceleration dimension as shown in (24) and (25).

$$\ddot{\theta}_{ref,c} = (\tau_{cmd,c} - \tau_{ext,c}) C_f \quad (24)$$

$$\ddot{\theta}_{ref,d} = (\theta_{cmd,d} - \theta_{m,d})(K_p + sK_d) \quad (25)$$

where $\tau_{cmd,c}$ is the torque command and $\theta_{cmd,d}$ is angular position command. In order to achieve properties of micro-macro bilateral control, both torque command and angular position command were set as zero. C_f is gain of force control, K_p and K_d is proportional gain of force control and differential gain of position control, respectively.

In order to control the motor, the acceleration control signal from model space is convert into real space of master and slave robot by applied inverse Hadamard matrix $(H_2)^{-1}$ (26) [23].

$$\begin{aligned}\begin{bmatrix} \ddot{\theta}_{ref,m} \\ \ddot{\theta}_{ref,s} \end{bmatrix} &= H_2^{-1} \begin{bmatrix} \ddot{\theta}_{ref,c} \\ \ddot{\theta}_{ref,d} \end{bmatrix} \\ H_2^{-1} &= \frac{1}{(f(\theta, \beta) + f(J_m, J_s, \alpha))} \begin{bmatrix} f(\theta, \beta) & f(J_m, J_s, \alpha) \\ 1 & -1 \end{bmatrix}\end{aligned}\quad (26)$$

where $\ddot{\theta}_{ref,c}$ and $\ddot{\theta}_{ref,d}$ are the acceleration control signal in common and differential modes, respectively. $\ddot{\theta}_{ref,m}$ and $\ddot{\theta}_{ref,s}$ are the acceleration control signals at the master and slave sides, respectively.

IV. Experimental Setup

The experiment setup for micro-macro bilateral control in task space for Delta Robot is verify by the result of proposed method to control two Delta Robots with different in size as shown in Fig. 8. The angular position of each motor is acquired by 17-bit increase encoder and force disturbance is estimated by disturbance observer. The control method is performed by PC with sampling time of 200 μs with soft realtime-OS windows 7 using 8 channels digital to analog

converter and 8 channels encoder counter. The controller program are written in C# language for better integrated development environment and human interface. The parameter of big and small robot used in this experiment are shown in Table 1 and Table 2, respectively.

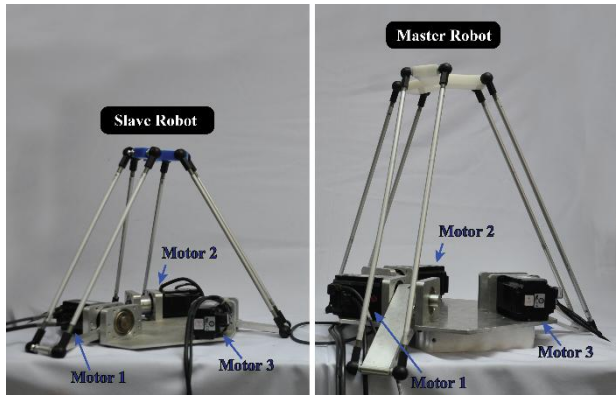


Fig. 8. Two size of robots used in experiment to verified proposed method

TABLE I
PARAMETER FOR BIG ROBOT

Symbol	Parameter's name	Value	Unit
I_n	Nominal Motor inertia	0.0000769	kg·m ²
I_u	Sum of motor inertia and structure inertia	0.000781	kg·m ²
K_n	Nominal Force coefficient	0.487	Nm/A
C_f	Force control gains	5	
K_p	Proportional gains of position control	500	
K_d	Derivative gains of position control	250	
G_{vm}	Gain of low-pass filter for velocity estimation	500	rad/s
G_{dis}	Gain of disturbance observer (encoder based)	500	rad/s
R	Radius of base plate	0.1585	m
r	Radius of travelling plate	0.09	m
L_1	Length of upper-arm	0.2	m
L_2	Length of fore-arm	0.587	m
M_u	Mass of upper-arm	0.673	kg
M_f	Mass of fore-arm	0.182	kg
M_b	Mass of bidirectional joint or ball joint	0.044	kg
M_t	Mass of travelling plate	0.236	kg
M_p	Mass of payload	0.0	kg

TABLE II
PARAMETER FOR SMALL ROBOT

Symbol	Parameter's name	Value	Unit
I_n	Nominal Motor inertia	0.000019	kg·m ²
I_u	Sum of motor inertia and structure inertia	0.000631	kg·m ²
K_n	Nominal Force coefficient	0.527	Nm/A
C_f	Force control gains	5	
K_p	Proportional gains of position control	500	
K_d	Derivative gain of position control	250	
G_{vm}	Gain of low-pass filter for velocity estimation	500	rad/s
G_{dis}	Gain of disturbance observer (encoder based)	500	rad/s

R	Radius of base plate	0.11925	m
r	Radius of travelling plate	0.06	m
L_1	Length of upper-arm	0.15	m
L_2	Length of fore-arm	0.417	m
M_u	Mass of upper-arm	0.174	kg
M_f	Mass of fore-arm	0.062	kg
M_b	Mass of bidirectional joint or ball joint	0.044	kg
M_t	Mass of travelling plate	0.084	kg
M_p	Mass of payload	0.0	kg

Value of motor inertia is calculated from SolidWork masses properties of designed upper-arm and inertial calculation following d'Alembert's principle. Reliable variable is available from technical document from manufacturer, mass and length of Delta Robot is acquired by measure the finished part of Delta Robot. Low-pass filter, gains of disturbance observer and control gains using signal to noise ratio method to determine suitable value [25]. Control gains is acquired by PID tuning system of Simulink Program with simplification.

The experiment is separated into two experiment of master and slave robot in same size and different side, first experiment is the robot with same size as shown in Fig. 9 using conventional micro-macro bilateral control in joint space compare with proposed micro-macro bilateral control in task space with position scaling gains (β) of 2 and force scaling gains (α) of 5, second experiment is the performance of proposed micro-macro bilateral control in task space with big robot as master and small robot as slave as shown in Fig. 10, position scaling gains (β) also set to 2 and force scaling gains (α) also set to 5. In order to easy understand of the result, the position and force of slave robot is multiple with 2 and 5, respectively to clarify the experiment result.

V. Experimental result

V.1. Micro-macro bilateral control on robot with the same size

In this experiment, the micro-macro bilateral control is setup for small robot as both master and slave robot is show in Fig. 9. The experiment result is shown in Fig. 11 for conventional micro-macro bilateral control and Fig. 12 for proposed micro-macro bilateral control method. The graph is separated into three part of X-axis, Y-axis and Z-axis on part (a), (b) and (c), respectively. The time is separated into two part of free movement (light yellow area) and small impedance applied on each axis (light green area). The performance of proposed method is slightly better than conventional method in not only position accuracy when the position is further away from origin and also the force response between master and slave robot where the conventional method show some distortion as the position is further away from origin. This result is cause by the fact that small robot have small workspace and the cosine value of some value is the same if that value is small. However, the small

displacement still cause problem in force space that is easy to observe. Moreover in impedance applied area, the position of travelling plate in conventional method show more error while proposed method have only problem on quick movement that can be compensated by increase the gains of position and force control. The offset in Z-axis and force damping is cause by gravity and soft realtime noise and still within acceptable range, respectively.

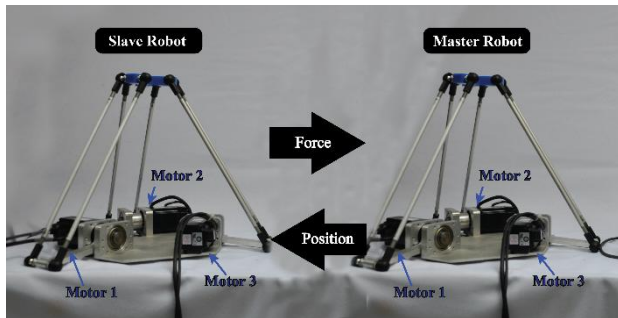


Fig. 9. Same size robot setup for first experiment

V.2. Micro-macro bilateral control on robot with the different size

In this experiment, the micro-macro bilateral control is setup for big robot as master and small robot as slave show in Fig. 10. The experiment result is show in Fig. 13 and do not include conventional method due to uncontrollable state and resonance as the force applied on slave robot. The graph is separated into three part of X-axis, Y-axis and Z-axis on part (a), (b) and (c), respectively. The time is separated into two part of free movement (light yellow area) and small impedance applied on each axis (light green area). The performance of proposed method show that even the size of master and slave robot is different, the proposed control method still be able to achieve the configuration of micro-macro bilateral control. The offset in Z-axis is cause by gravity that applied on structure.

VI. Conclusion

This thesis has present a new approach for micro-macro bilateral control in Delta Robot that has nonlinear kinematic and dynamic model with force estimation using disturbance observer to replace force sensor and reduce the complexity of dynamic system calculation of Delta Robot. The disturbance observer with proper dynamic model is able to observe the external force applied on travelling plate while eliminate majority of gravity using gravity compensation from mathematic. The proposed task space micro-macro bilateral control in delta robot verified the possibility to use both bilateral control and micro-macro bilateral control in difference workspace by transfer the data back and forward using only mathematic model. Delta robot with micro-macro bilateral control shown potential to use as human interface and able to store or transfer experience of

human from location to location in three dimensional space. Moreover, this properties enable robot to learn the position and force from human to perform certain task and open new approach in AI and computer learning to actively select the best position and trajectory planning from previous performed task. The travelling plate of Delta Robot achieved position ratio of position scaling gains (β) in all three dimensions while second law of Newton or Newton law of action and reaction is scaled by force scaling gain (α). The reference acceleration of master and slave robot is obtained by applied invert Hadamard matrix and Z-axis is shifted to clarify the result.

This technology provide possibility to build 3 dimensional movement robot which have ability to provide sensitivity of touch and reduce the noise from human hand due to high impedance in Z-axis of delta robot which is importance in work such as minimal invasive surgery, increase accuracy and safety system of industrial robot.

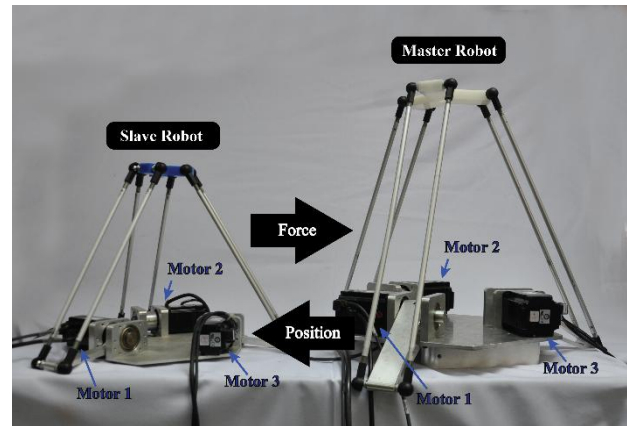


Fig. 10. Different size robot setup for second experiment

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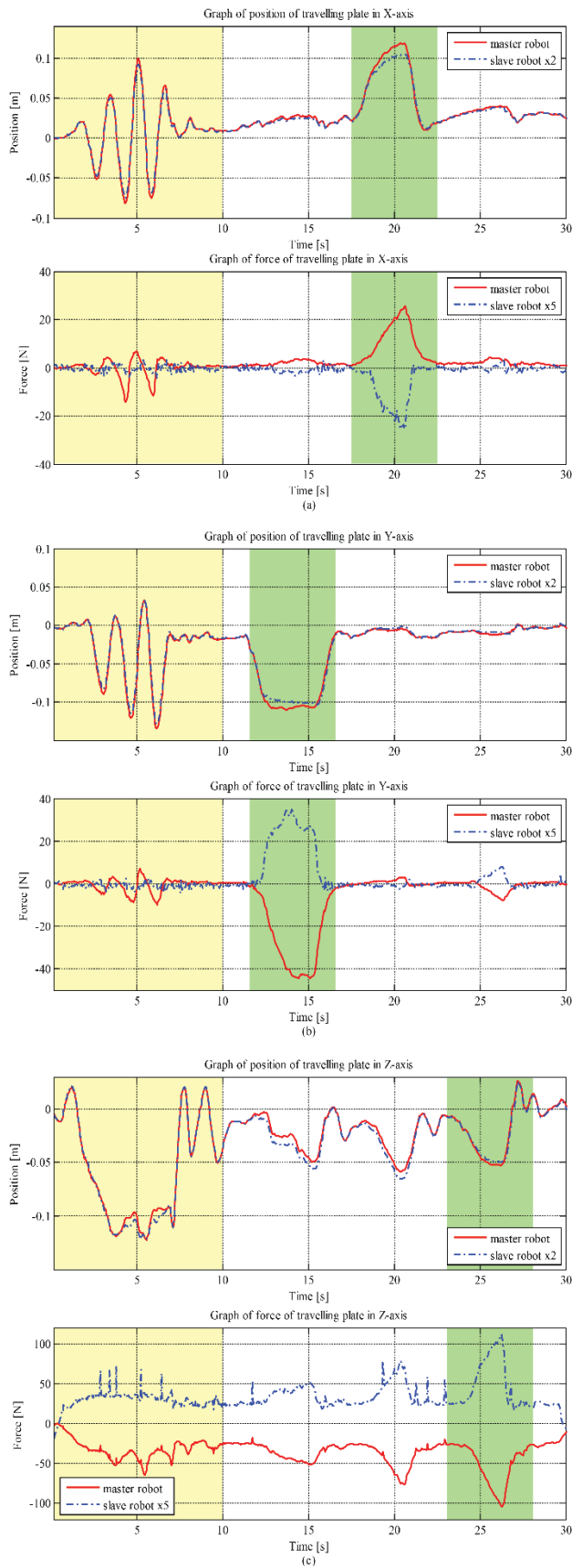


Fig. 11. Position and Force response with same size robot at travelling plate of master (red) and slave multiply position and force by 2 and 5, respectively (blue) with conventional micro-macro bilateral control separate in (a) X-axis, (b) Y-axis and (c) Z-axis.

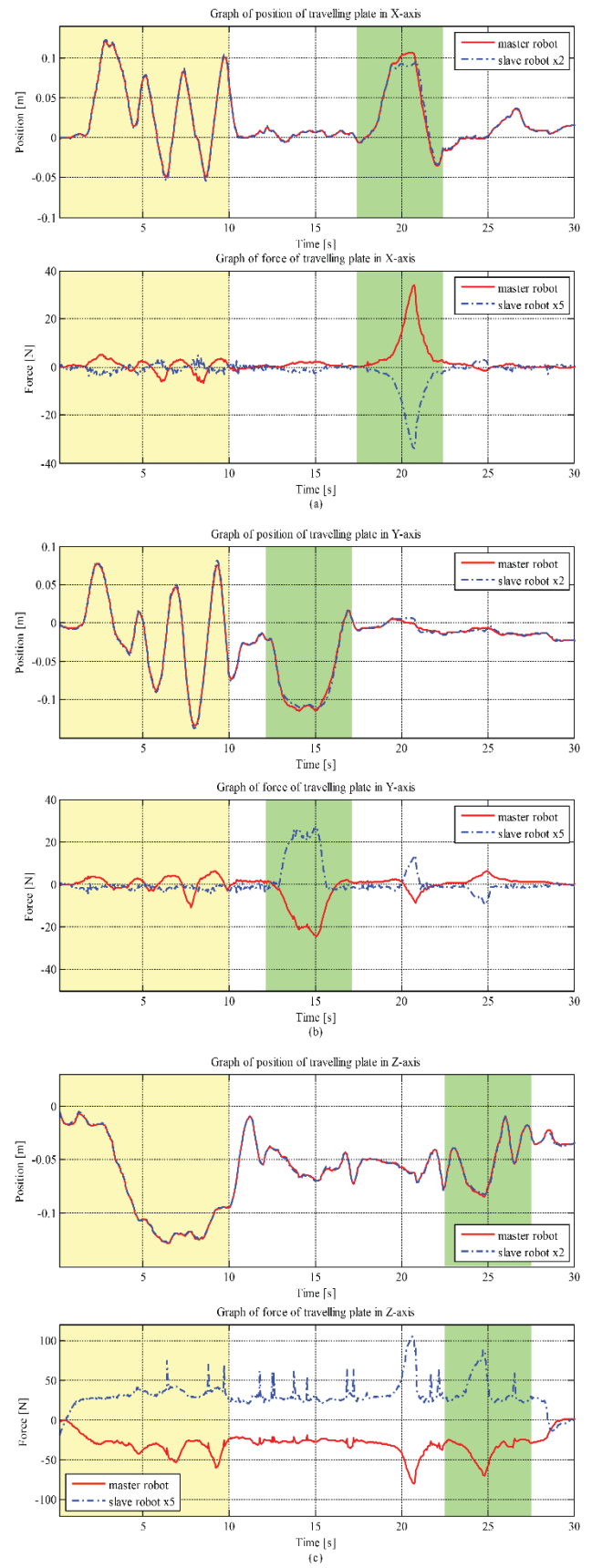


Fig. 12. Position and Force response with same size robot at travelling plate of master (red) and slave multiply position and force by 2 and 5, respectively (blue) with proposed micro-macro bilateral control separate in (a) X-axis, (b) Y-axis and (c) Z-axis.

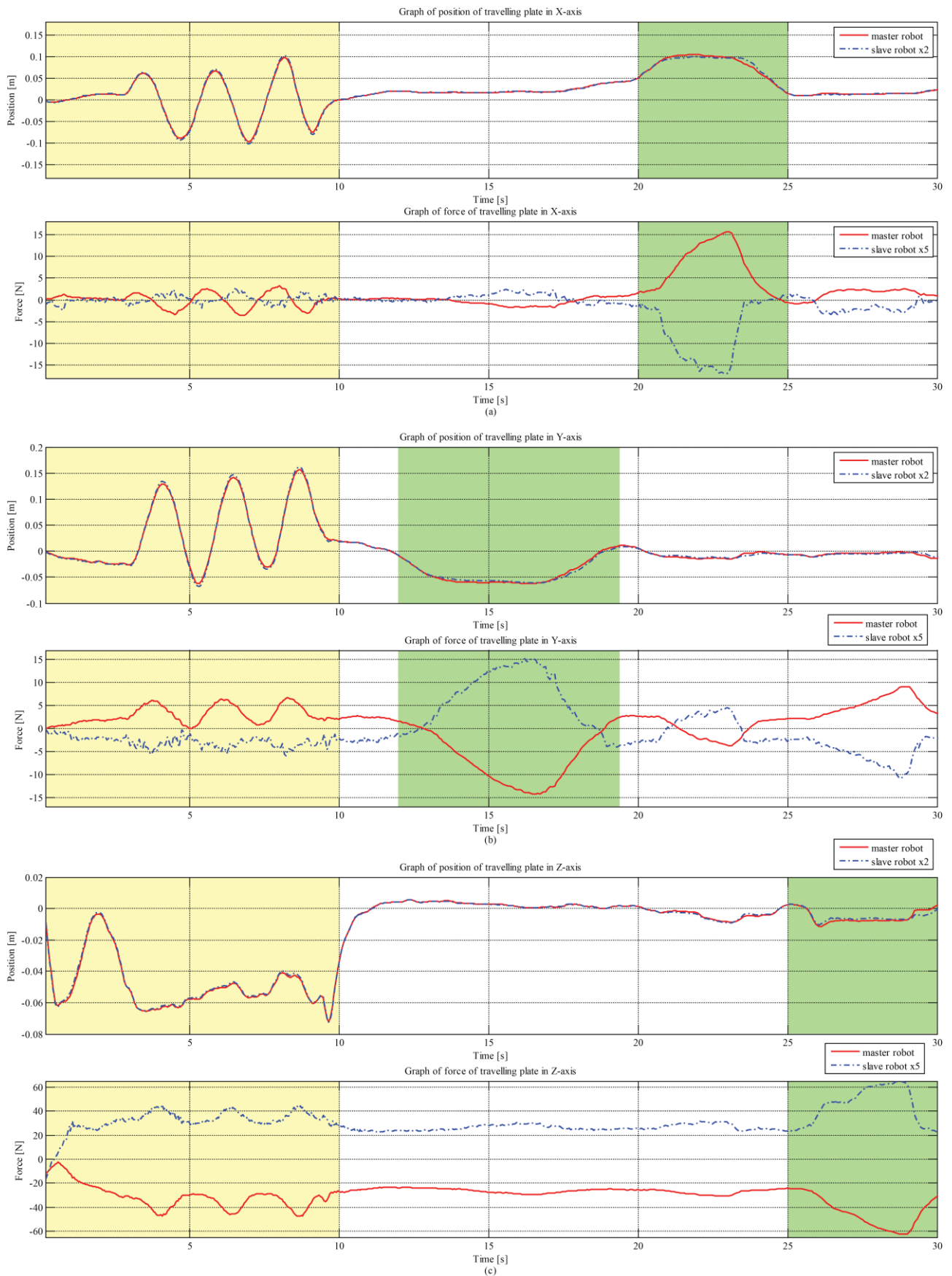


Fig. 13. Position and Force response with different size robot at travelling plate of master (red) and slave multiply position and force by 2 and 5, respectively (blue) with proposed micro-macro bilateral control separate in (a) X-axis, (b) Y-axis and (c) Z-axis.

Bilateral Control Based on Disturbance Observer of Delta Robot with Gravity Compensation

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Keywords: Delta robot, Bilateral control, Disturbance observer, Gravity compensation

Abstract. Recently, delta robots is widely used in many industrial application because the structure of delta robot is close loop chain and have properties of high rigid body and fast movement. However, the moving part of delta robot is arranged in pattern that influenced by gravity and has an impact on control system. In this paper, we proposed force and position control in master-slave configuration while compensate gravity. The control system using disturbance observer (DOB) to estimate sum of action/reaction force and gravity force of master-slave delta robot instead of the force sensors. The external force on travelling plate of delta robot is estimated by disturbance force on upper and computational gravity force from dynamic model. Moreover, the delta robot may various in size due to the conditioning of workspace, therefore the method to control the task space is proposed. The simulation is conduct to verify the control system, compare the position and force of travelling plate with and without gravity compensation.

Introduction

The delta robot is widely used in many applications which have a high accuracy such as industry and medical application to use with user. User has ability to control an operation to match with the situation while robot has more accuracy and precision than user. So the combined operation between user and robot together can improve the performance and efficiency.

Bilateral control system is a method to control bilaterally with the same position and force. The master and slave robot based on bilateral control system are used in many haptic communications. To design the bilateral control system should be design to confirm the human contact because human has many degrees of freedom while robot has a degree of freedom due to the design. Due to high noise and low bandwidth of force sensor, the disturbance observer is used to instead of force sensor.

Considering force on structure of delta robot, each component of the delta robot has mass in its structure and lead to gravitational disturbance, and also has external force. Gravitational is degrading the accuracy of the movement and force especially the upper arm of the delta robot. Due to the DOB can assess external and gravity force, so we eliminate gravity force by calculate from dynamics model to compensate it. So which improve the accuracy and performance of the movement and force response of the delta robot.

This paper is organized as follows. First, we introduce model of delta robot and analyze force of structure in Introduction. Second, proposed kinematics for delta robot in Delta Robot Kinematics. Third, proposed dynamics of delta robot in Delta Robot Dynamics. Fourth, proposed Designing the Bilateral Controller. Fifth, Simulation setup for proposed bilateral control and variables for Simulink simulation in Simulation Setup. Final summarizes this paper in Conclusion.

Delta Robot Kinematics.

A. Forward Kinematics. Position of traveling plate can be mathematically calculated by angular position of actuated revolute joints, this process called forward kinematic[1]. Consider three spheres each with the center at the ball joint (C_i) of each robot arm, and with the forearms lengths (L_b) as radius which shown in Fig. 1 and 2. The center position of the travelling plate (x,y,z) is

located at an intersection of three spheres. As result, center of ball joint (C_i) represented by (1), (2) and (3), respectively.

$$x_i = (r_a - r_b + L_b \cos \theta_i) \cos \alpha_i \quad (1)$$

$$y_i = -(r_a - r_b + L_b \cos \theta_i) \sin \alpha_i \quad (2)$$

$$z_i = -L_b \sin \theta_i \text{ for } i=1,2,3 \text{ and } \alpha_1=0, \alpha_2=2\pi/3, \alpha_3=4\pi/3 \quad (3)$$

Thus, three sphere equations must be solved simultaneously for (x,y,z) position, as in Eq.(4). There will be two possible solutions that describe the two intersection points of the three spheres. We will choose solution with negative z coordinate.

$$(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2 = L_b^2 \text{ for } i=1,2,3 \quad (4)$$

B. Inverse Kinematics. For angular position of each motors could be find with position of traveling plate in delta robot. Consider two circle to find the intersect position in yz plane (y_i, z_i) shown in Fig. 1, therefor the point with higher y -axis value is selected. As a result, the equation for joint position in yz plane is represented by (3) and (4).

$$(y_i - r_a)^2 + z_i^2 = L_a^2 \text{ and } (y_i - (r_a + y))^2 + (z_i - z)^2 = L_{b,yz}^2 \quad (5)$$

Where $L_{b,yz}$ is projection of forearm on yz plane, from y_i and z_i , the angular position of motor 1 are calculated by (6). Angular position of other motors are calculated using rotation position of x , y and z have rotate $2\pi/3$ and $4\pi/3$

$$\theta_i = \tan^{-1} \left(\frac{z_i}{y_i - r_a} \right) \quad (6)$$

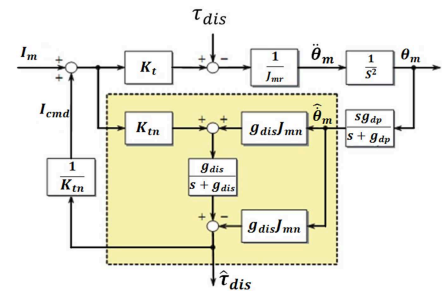
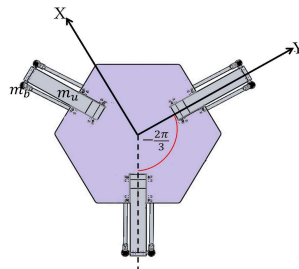
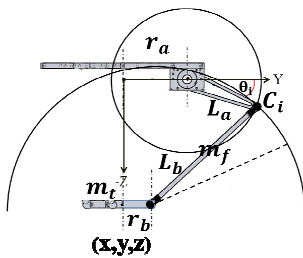


Fig.1. yz plane of delta robot

Fig.2. xy plane of delta robot

Fig.3. Disturbance Observer

Delta Robot Dynamics

The well-known dynamic for delta robot is express by motor torque. The dynamic model is simplified in to mainly four component torque of motor include torque from gravity force on traveling plate (τ_{gt}), torque from gravity force at center of gravity for upper arm (τ_{gu}), torque from inertial force on traveling plate (τ_{it}) and torque contribution from each upper arm to the actuated joints (τ_{iu}). Gravitational torque is calculated separately between top-link part and bottom-link part of robot which bottom-link part have total contribution mass of traveling plate (m_{ts}) compose traveling plate mass (m_t), pay load mass (m_p) and forearm mass (m_f). Top-link part have total contribution mass of upper arm (m_{us}) consist upper arm mass (m_u), ball joint mass (m_b) and 2/3 of forearm mass.

$$\tau_{gt} = J^T m_{ts} [0 \ 0 \ -g]^T \text{ and } \tau_{it} = J^T m_{ts} [\ddot{x} \ \ddot{y} \ \ddot{z}]^T \quad (7)$$

Where J is Jacobian matrix [1], it is a mapping from motor angular velocity in joint space to velocity in Cartesian space.

$$\tau_{gu} = m_{us} (-g) C_g [\cos \theta_1 \ \cos \theta_2 \ \cos \theta_3]^T \quad (8)$$

$$\tau_{iu} = I_u \ddot{\theta}_i \quad (9)$$

Where C_g is center of gravity for upper arm is represented by (10), I_u is inertia matrix of arm in joint space [1], and g is gravitational constant.

$$C_g = L_a \frac{\frac{m_u}{2} + m_b + 2m_f/3}{m_{us}} \quad (10)$$

Thus, overall dynamic equation of the delta robot is represented by (11)

$$\tau + \tau_{gu} + \tau_{gt} = \tau_{iu} + \tau_{it} \quad (11)$$

Designing the Bilateral Controller

A. Disturbance Observer. This paper show the DOB which used instead of force sensor. It has been confirmed that a stable force control loop can be obtained when a DOB is implemented as the feedforward control for a disturbance torque compensation loop [2]. The disturbance torque is obtained from the motor's current (I_m), torque constant (K_t), motor and robot inertial (J_{mr}), and the second derivative of the position signal ($\ddot{\theta}_m$), as shown in (12). The structure of DOB is shown in Fig. 3.

$$J_{mr}\ddot{\theta}_m = I_m K_t - \tau_{dis} \quad (12)$$

$$\hat{\tau}_{dis} = \frac{g_{dis}}{g_{dis} + s} (K_{tn} I_m + g_{dis} J_{mn} \dot{\theta}_m) - g_{dis} J_{mn} \dot{\theta}_m \quad (13)$$

Where g_{dis} denotes the cut-off frequency of the low pass filter.

B. Bilateral Control System. The bilateral control system is the method to control robot bilaterally with the same position and force. The robot is consist of master delta robot and slave delta robot. The goals of bilateral control ,is transfer sense between two place by using master robot to simulate the force of slave robot that interacted by environment based on third law of Newton or Newton law of action and reaction, as shown in (14). Moreover, the position in Cartesian space of master delta robot and slave must have the same direction distance, as shown in (14).

$$\hat{\tau}_{mext,i} = -\hat{\tau}_{smext,i} \text{ and } \hat{\theta}_{m,s,i} = \hat{\theta}_{s,i} \text{ for } i=1,2,3 \quad (14)$$

Where $\hat{\tau}_{mext,i}$ are approximation external torque of master delta robot, $\hat{\tau}_{smext,i}$ are approximation external torque of slave on base master. $\hat{\theta}_{s,i}$ are angular position of slave ,and $\hat{\theta}_{m,s,i}$ are angular position of master on base slave.

Bilateral control can be describe in two control modes, common mode and differential mode. It can control torque and position simultaneously by using Hadamard matrix (H_2). Hadamard matrix is used to convert torque and position in real space to virtual space. That is torque and position in real space is convert to virtual space by using (15)

$$\begin{bmatrix} \hat{\tau}_i^c \\ \hat{\tau}_i^d \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \hat{\tau}_{mext,i} \\ \hat{\tau}_{smext,i} \end{bmatrix} = H_2 \begin{bmatrix} \hat{\tau}_{mext,i} \\ \hat{\tau}_{smext,i} \end{bmatrix} \text{ and } \begin{bmatrix} \hat{\theta}_i^c \\ \hat{\theta}_i^d \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \hat{\theta}_{m,s,i} \\ \hat{\theta}_{s,i} \end{bmatrix} = H_2 \begin{bmatrix} \hat{\theta}_{m,s,i} \\ \hat{\theta}_{s,i} \end{bmatrix} \quad (15)$$

However, the conversion from virtual space to real space, can be use Inverse Hadamard matrix (H_2^{-1}). which shown in Eq. (16).

$$\begin{bmatrix} \ddot{\theta}_{ref1} \\ \ddot{\theta}_{ref2} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}^{-1} \begin{bmatrix} \ddot{\theta}_{ref}^c \\ \ddot{\theta}_{ref}^d \end{bmatrix} = H_2^{-1} \begin{bmatrix} \ddot{\theta}_{ref}^c \\ \ddot{\theta}_{ref}^d \end{bmatrix} \quad (16)$$

Simulation Setup. In this simulation setup, the master-slave delta robot is used. Each delta robot is consist of 3 motors and disturbance observer is used to estimate the external torque. The simulation is consist of two parts , both master-slave delta robot with gravity compensation and master delta robot without gravity compensation have any disturbance force at Z axis. The block diagram of simulation setup is shown in Fig.4.

From Fig 5a, force responses of master-slave delta robot are effected by gravitational. So, this makes force response of master delta robot isn't according to input disturbance. In Fig.5b, force response can be meet the targets set, due to the robot aren't effected by gravitational.

From Fig. 6a, position of delta robot is moved down in 1 second and moved up and down slightly according to input disturbance. But the results are not satisfied enough.

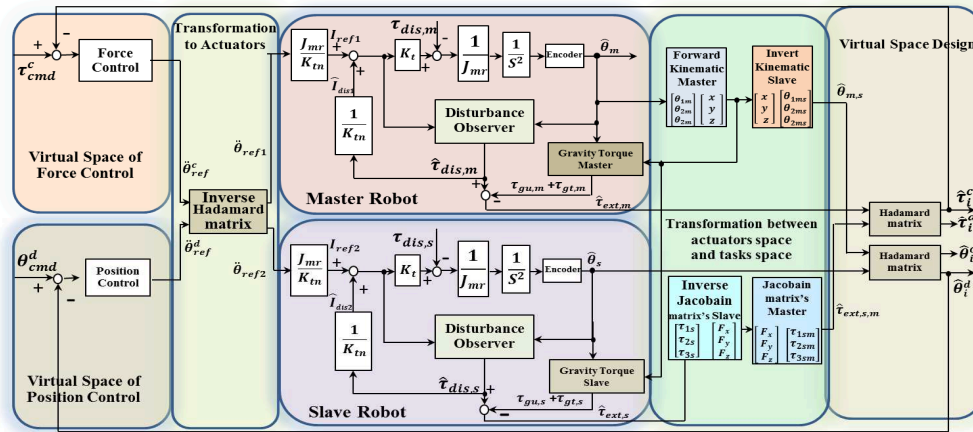
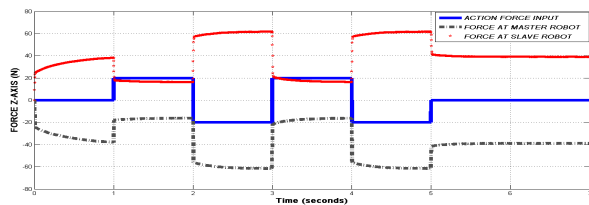
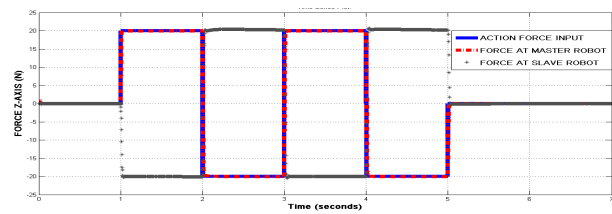


Fig. 4. Bilateral Control of Delta robot with gravity compention

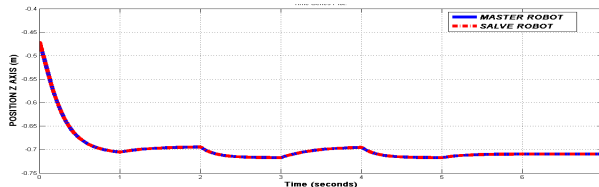


(a) With out gravity compensation

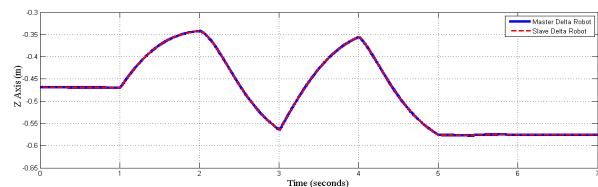


(b) With gravity compensation

Fig. 5. Force response of Delta robot (Z-Axis)



(a) Without gravity compensation



(b) With gravity compensation

Fig. 6. Position of Delta robot (Z-Axis)

Conclusion

In this paper propose the bilateral control based on DOB of master-slave delta robot with various size and gravity compensation. Gravity affects the structure of the delta robot in vertical axis. It makes force response of master and slave robot different from input disturbance. So, gravity compensation is used to calculate gravitational force and compensate back to eliminate the effect of gravity. For the future work, this method can be used in many applications such as medical instrument and industrial robot.

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An Analysis of Force Response by Using Spectrogram

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Keywords: Disturbance Observer, Bilateral Control System, Master-Slave Robot, Short-Time Fourier Transform, Spectrogram, Wrist Rehabilitation Robot

Abstract. In haptic technology, robot has to contact with objects and human operator. The robot systems must be flexible systems, high accuracy and precision during the operation for safe the human operator. So, analysis of the force response is a necessary ability to design the controller of the robot systems. This paper proposes a methodology to analyze force response by mean of spectrogram analysis. The master-slave robot based on bilateral control is used by human operator. Disturbance Observe (DOB) is used to estimate the force response instead of force sensor to improve the performance of the whole system. Finally, force response is analyzed by spectrogram. The availability of the proposed method is shown in an experiment.

Introduction

Recently, robot is used in many applications to support human operator such as industrial robot, surgical robot and rehabilitation robot. During the operation, robot has to contact with many kind of objects or human operator. So, robot must be operated with high safety and accuracy to safe the human operators. Therefore, force response of the robot is necessary to design the controller of the robots. For these reasons, the analysis of the force response has become more interesting method.

Generally, a force sensor is widely used to measure the external force. However, force sensor has a limitation which degrade the performance of the system, for example, a force sensor has a low bandwidth, high noise level and high costs. Thus, Disturbance Observer (DOB) is used to estimate the external force instead of force sensor to improve the robustness of the whole system [1].

Bilateral control system which consist of master and slave robot is used in many haptic communication system [2]-[3]. The slave robot is used to contact with the environments and sent force response back to the human operator through the master robot.

This paper proposes the method by analysis the force response through the spectrogram. The wrist rehabilitation master-slave robot is used in the experiment. The torque response of master-slave robot motors are estimated by DOB. Then the torque response are analysis by spectrogram [4]. This paper is organized as follows. The section 2 explains the DOB and bilateral control system of master-slave robot. In section 3, Short-Time Fourier Transform and spectrogram analysis is described. The experimental results are represented in section 4. Finally, the last section summarized the paper.

Bilateral Control System based on Disturbance Observer

A. Disturbance Observer. The goal of force control is to control the external force. So, force sensor is widely used to measure the external force. However, force sensor have a limitation which degrade the performance of the whole system. So, Disturbance observer (DOB) is used instead of force sensor to estimate disturbance force at motor and feedback and compensate for improve the robustness and bandwidth of the system. The structure of DOB is shown in Fig 1.

Where M denotes the mass of the motor, K_t denotes the force coefficient, G_{dis} is the cut-off frequency of the low-pass filter. $\ddot{\Theta}_m$, $\dot{\Theta}_m$ and Θ_m represent angular acceleration, velocity and

position of the motor respectively. τ_{dis} is disturbance torque and $\hat{\tau}_{dis}$ is the disturbance torque which estimated by DOB.

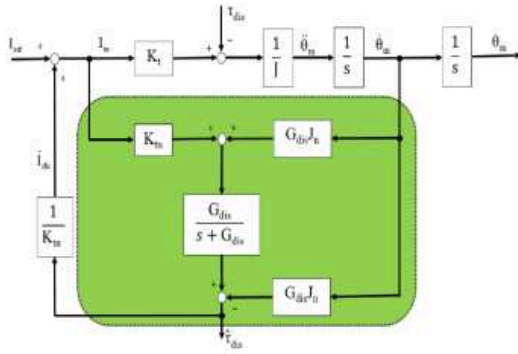


Fig 1. Disturbance Observer (DOB)

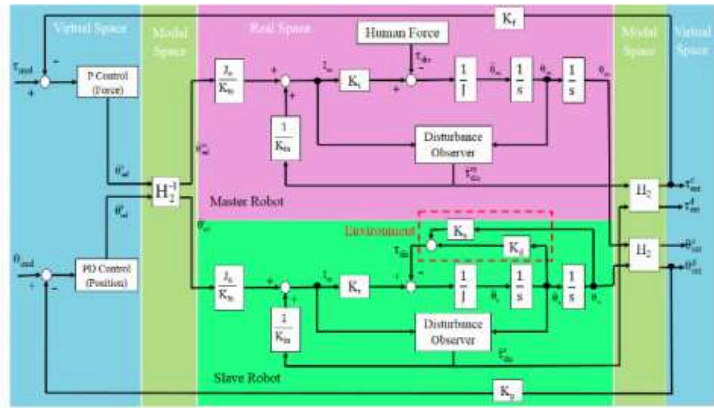


Fig 2. Bilateral Control System

B. Bilateral Control System. The bilateral control system is consists of master and slave robot which control bilaterally. Its control goals are represented as follows,

$$\tau_m + \tau_s = 0 \quad (1)$$

$$\theta_m - \theta_s = 0 \quad (2)$$

According to Newton's law of action and reaction, torque at master side is equal to slave side in the opposite direction which shown in eq. (1). Moreover, the position of the master and slave robot must be similar which shown in eq. (2).

To control torque and position simultaneously, two control modes namely common mode and differential mode are used. Torque and position in each mode are controlled in an acceleration dimension. Therefore, Hadamard matrix is used to convert from real space to virtual space as follows,

$$\begin{bmatrix} \hat{\tau}_{ext}^c \\ \hat{\tau}_{ext}^d \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \hat{\tau}_{dis}^m \\ \hat{\tau}_{dis}^s \end{bmatrix} = H_2 \begin{bmatrix} \hat{\tau}_{dis}^m \\ \hat{\tau}_{dis}^s \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} \hat{\theta}_{ext}^c \\ \hat{\theta}_{ext}^d \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \hat{\theta}_{dis}^m \\ \hat{\theta}_{dis}^s \end{bmatrix} = H_2 \begin{bmatrix} \hat{\theta}_{dis}^m \\ \hat{\theta}_{dis}^s \end{bmatrix} \quad (4)$$

Eq. (3) – (4) represent common and differential mode of torque and position respectively. The subscript c is a common mode, subscript d is a differential mode, subscript m is a master robot and subscript s is a slave robot. The structure of bilateral control system is shown in Fig 2.

Analysis by using Spectrogram

A. Short-Time Fourier Transform. The Fourier Transform is a basic theory to extract the frequency component of stationary signal which parameters are constant over time. But in real world, the signals are non-stationary which parameters are vary with time. So, Fourier Transform is completely losing time information. To deal with the non-stationary signal, Short-Time Fourier Transform (STFT) which show in Fig 3 is applied in this paper instead of Fourier Transform. Short-Time Fourier Transform equation is shown as follows,

$$X_{STFT}(e^{j\omega}, n) = \sum_{m=-\infty}^{\infty} X(n-m)w(m)e^{-j\omega m} \quad (5)$$

$X(n)$ is separated into short parts by using window function $w(n)$. Each window function must overlap between other windows. Then the window function is shifted in time-domain. The Results of each window is used to calculate the spectrogram by computed the squared magnitude of the STFT.

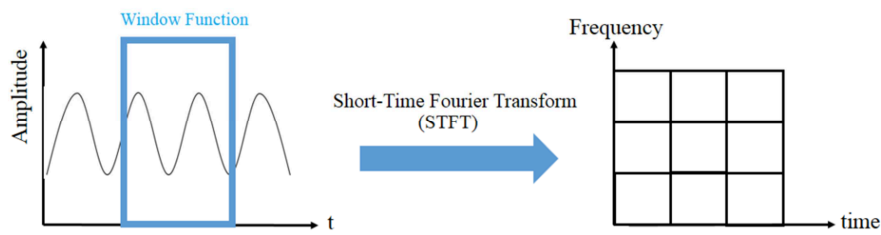


Fig 3. Short-Time Fourier Transform (STFT)

B. Spectrogram. Spectrogram is a graph with three dimensions. There are X, Y and Z axis which represent time, frequency and amplitude of the signal respectively. Thus, spectrogram can show time and frequency information at the same time. Considering 2 dimension on X-Y plane, a high amplitude of torque response is represented by warm colors. While a low amplitude of torque response is represented by cool colors.

Experiment and Result

A. Experimental Setup. The proposed method is applied to the wrist rehabilitation robot which shown in Fig 4. Master and slave wrist rehabilitation robot are used. Each of robot is consist of two servo motors. Upper motors 1 and 3 are controlled bilaterally same as lower motors 2 and 4 which shown in Fig 5.

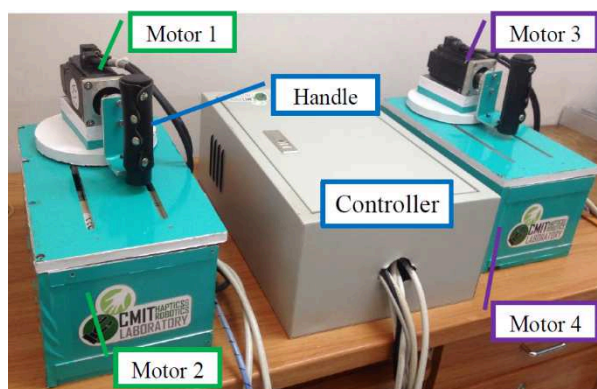


Fig 4. Wrist Rehabilitation Robot

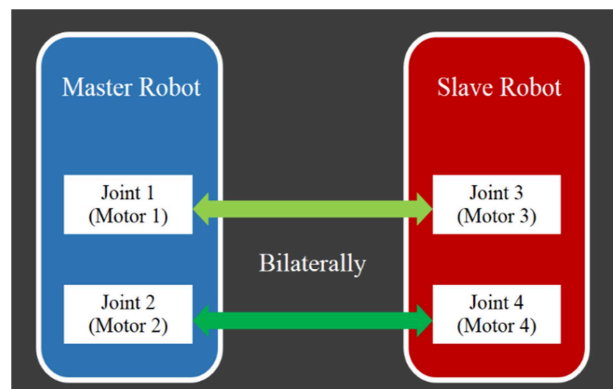


Fig 5. Wrist Rehabilitation Robot System

B. Experimental Results. Fig 6 shows the torque response of motor 1 and 3 which is master and slave robot. Fig 7 shows the torque response of motor 2 and 4 which is master and slave robot. In this experiment, motor 1 and 2 are used in master robot while motor 3 and 4 are used in slave robot. Torque of motor 1 is equal to motor 3 in an opposite direction same as motor 2 and 4.

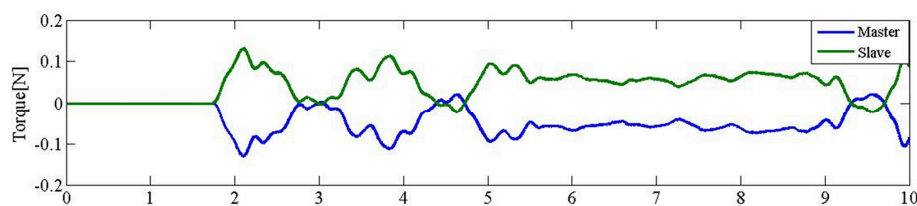


Fig 6. Torque response of motor 1 and 3

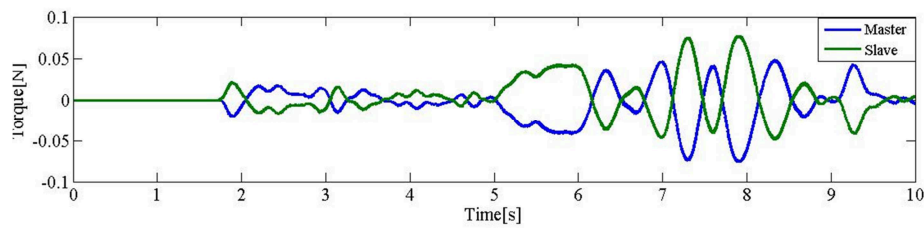


Fig 7. Torque response of motor 2 and 4

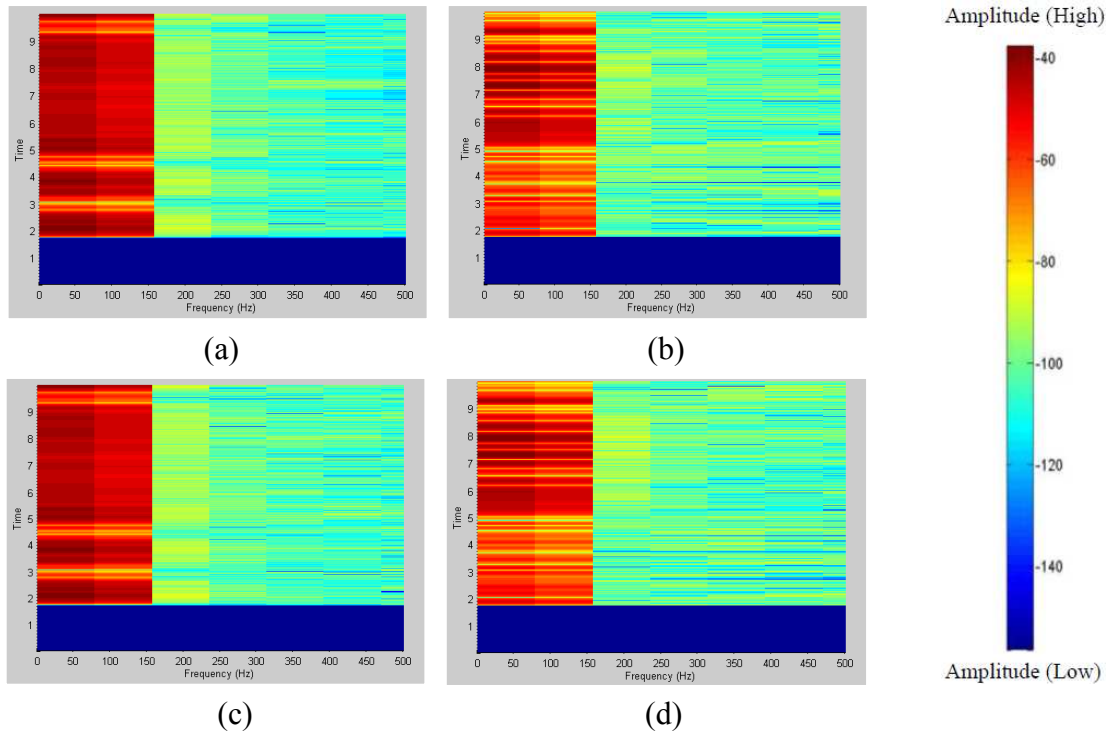


Fig 8. Spectrogram of motor's torque. (a) Motor 1. (b) Motor 2. (c) Motor 3. (d) Motor 4.

Fig. 8 shows the spectrogram of torque response. (a), (b), (c) and (d) are torque response of motor 1, 2, 3 and 4 respectively. According to the results, motor 1 and 3 are controlled bilaterally so, spectrogram of motor 1 is similar to motor 3, in the same way as spectrogram of motor 2 and motor 4. From fig. 6, torque response of motor 1 and 3 at period 2, 4 and 5 are higher than other period. So, the intensity of color at period 2, 4 and 5 are higher than other period which show in Fig 8(a) and (c).

Conclusion

This paper presents the analysis of force response by using spectrogram. From the experimental results, the spectrogram analysis shows the vibrations of force response at the different frequency. For the future work, the proposed method can apply with many applications such as wrist rehabilitation. Wrist rehabilitation robot is used to collect data of people who are normally and show by spectrogram. Physiotherapist can check wrist's abnormality by using the data of patient to compare with previous data. In industrial work, robots are used to knock the objects and collect the force response data. By the spectrogram analysis, the objects can be discriminated. So, robots can know what object that the robot is contacted with.

Acknowledgement

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Sensor Fusion of Acceleration and Position for Improved External Force Estimation of Flexible Robot System

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Abstract

Force estimation is one of the most important techniques in the robot control application. In this research, acceleration sensor based load-side disturbance observer (ALDOB) is proposed and developed by integrating an acceleration sensor on the load side and the optical encoder on the motor side in order to estimate external force. The enhancement of the force estimation was found to increase. Good estimation of force and robust force control could be obtained using ALDOB observer. The simulation results are provided to illustrate the performance of the proposed algorithms. A flexible robot model was established to simulate the robot dynamic in force control, and the results agree with the analysis.

Key words: Force control, Disturbance Observer, Acceleration sensor, Kalman filter

1. Introduction

Recently, robotic systems find widespread application in the industrial factory, automation and spacecraft, as well as medical devices^{(1)–(3)}. In order to interact with an unknown environment or human, the development of robotic systems focused on the using of force sensor⁽⁴⁾. Force sensors on the end effectors send signals of external force to the controller to control the force command. The distinguishing characteristic of a force sensor structure is that it cannot compensate for vibration effect that add to the signal due to the soft structure of strain gauge. Moreover, the signal of force sensor is corrupted not only by disturbance noise but also by the limitation of the bandwidth of the sensor⁽⁵⁾.

In order to overcome this problem, a disturbance observer (DOB)^{(6)–(7)} has become a preferred approach for improving accuracy of the force estimation. It has been shown that a superior performance with robustness can be achieved by using the disturbance observer. Bandwidth of the force estimation can be designed more conveniently in observer, often by a simple adjustment of the cut-off frequency in the low-pass filter. However, it does not suitable for the two-mass system due to the structure vibrating in resonance^{(8)–(11)}. Two mass system consists of a motor and load connected by a spring as shown in the Fig. 1. Its elasticity of mechanism causes resonance in the system. The conventional PID controller does not perform well when the plant system has a resonance structural vibration. Therefore, it is necessary to design a new approach that guarantees the robustness and suppress vibration.

A load-side encoder may be often implemented to measure the load position in order to suppress vibration of the system. Load-side based disturbance observer^{(12)–(13)}, then, have the obvious advantage of greater accuracy than disturbance observer. However, parameter identification of spring coefficient is very difficult to estimate.

A new estimation method, the multi-encoder based dis-

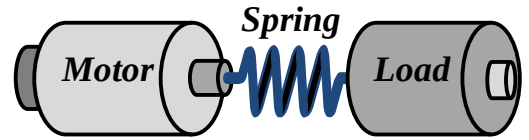


Fig. 1. Two-mass system.

turbance observer (MEDOB)⁽¹⁴⁾, has been introduced as a new way to estimate the load-side external force. In the our previous research, the proposed observer is not necessary to identify the spring coefficient. It is simple to design and easily implemented into the system with the mechanical resonance. However, it is difficult to attach the encoder on the load side of the robot system.

In this research, a new combined observer technique, named acceleration sensor based load side disturbance observer (ALDOB), has been proposed by using acceleration sensor on the load side and encoder on the motor side. Kalman filter and disturbance observer are designed to estimate the load-side external force. The mounting wax is used to mount a piezoelectric acceleration sensor on the end-effector of the robot. The space requirement for sensor is very small. Thus, it is suitable for attaching sensor on the load-side of robot system.

This paper is organized as follows. We introduce the modeling of two-mass system in Section 2. The structure of the disturbance observer, load-side disturbance observer, multi-encoder based disturbance observer and acceleration sensor based load-side disturbance observer is described in Section 3. The simulation results with discussion are shown in Section 4, which is followed by the conclusion in Section 5.

2. System Description of Two Mass System

Generally, the mechanics of machine and robot system often consist of a motor M and a load L connected by a flexible

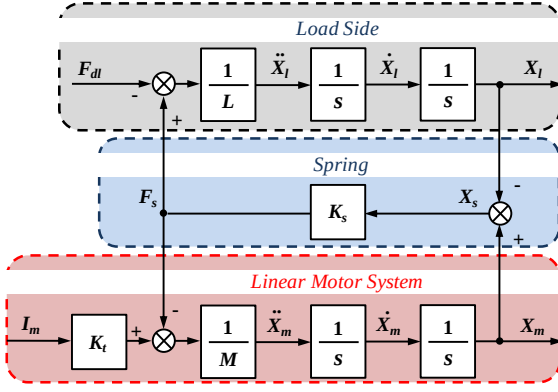


Fig. 2. Modeling of two-mass system.

structure to transmit the actuator torque to a distant joint as shown in Fig. 1⁽⁸⁾⁻⁽¹¹⁾. Since the actuator is connected to the load side with a transmission mechanism, its elasticity causes resonance in the system. Therefore, the elasticity of flexible robot is realized under assumptions that it can be modeled by spring coefficient K_s and mass system. A block diagram of the linear motor with two-mass system that controls under the ideal current source is shown in Fig. 2. The dynamic equation of the linear motor is described by:

$$\ddot{X}_m = -\frac{K_s}{M}X_s + \frac{K_t}{M}I_m, \dots\dots\dots (1)$$

$$\ddot{X}_l = \frac{K_s}{L}X_s - \frac{1}{L}F_{dl}, \dots\dots\dots (2)$$

$$\dot{X}_s = \dot{X}_m - \dot{X}_l \dots\dots\dots (3)$$

where subscripts m and l denote the motor side and load side, respectively. F_s and F_{dl} are the spring force and the external force on the load side. K_t is the force coefficient, I_m is the current, X_s is the torsional position from the position of the motor X_m and the position of the load X_l , M and L denote the equivalent mass of the linear motor and load mass, respectively. Naturally, this flexible transmission can negatively affects the overall performance in terms of increased vibrations. From Fig. 2, the transfer function from current reference I_m to the velocity of motor side $\dot{X}_m$ and the transfer function from current reference I_m to the velocity of load side $\dot{X}_l$ can be calculated as follows,

$$\frac{\dot{X}_m}{I_m} = \frac{\frac{K_t}{M}(s^2 + \frac{K_s}{L})}{s^3 + (\frac{K_s}{L} + \frac{K_s}{M})s}, \dots\dots\dots (4)$$

$$\frac{\dot{X}_l}{I_m} = \frac{\frac{K_t K_s}{ML}}{s^3 + (\frac{K_s}{L} + \frac{K_s}{M})s} \dots\dots\dots (5)$$

Then, the anti-resonance ω_{ar} and resonance frequencies ω_r can be described as follows,

$$\omega_r = \sqrt{\frac{K_s}{L} + \frac{K_s}{M}}, \dots\dots\dots (6)$$

$$\omega_{ar} = \sqrt{\frac{K_s}{L}} \dots\dots\dots (7)$$

3. Estimation of Disturbance and External Force on the load side

3.1 Disturbance Observer (DOB) Consequently,

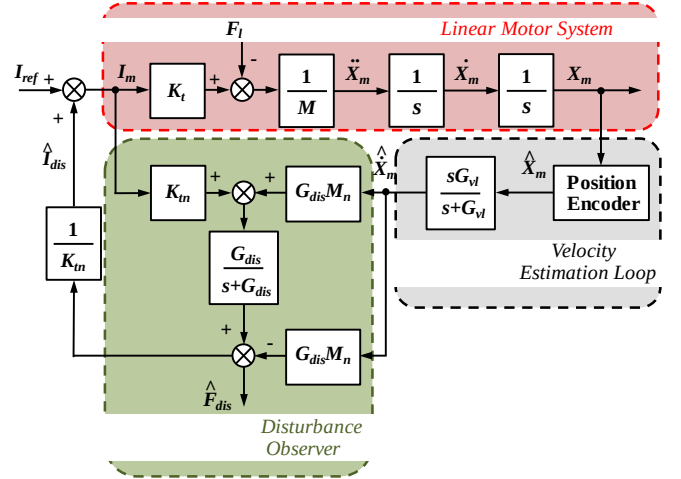


Fig. 3. Disturbance observer.

a disturbance observer has been used, not only for improving the robustness and bandwidth of the control system, but also for estimation the external force for examples,⁽⁶⁾⁽⁷⁾. It has been confirmed that a robust force control can be obtained, when a disturbance observer is implemented as the feed forward control for a disturbance force compensation loop. Here, the disturbance force on the motor side F_l is defined as,

$$F_l = F_{fm} + D_m \dot{X}_m + F_s + \Delta M \ddot{X}_m + \Delta K_t I_m \dots\dots (8)$$

where, the resistive force which the direction is opposite to the motor force is the summation of friction force F_{fm} , viscous friction $D_m \dot{X}_m$ and the spring force F_s . $\Delta M \ddot{X}_m$ is the variation torque due to changed mass, $\Delta K_t I_m$ is the force ripple due to space harmonics.

In this research, it is assumed that the influence of the friction force is very small by using a small-size of linear motor; thus, the spring force has almost the same value of the disturbance force. Disturbance observer is an external disturbance estimation algorithm that is based upon motor current and velocity information as shown in

$$\hat{F}_l = \frac{G_{dis}}{s + G_{dis}} \left(K_{tn} I_m + G_{dis} M_n \hat{X}_m \right) - G_{dis} M_n \hat{X}_m \dots\dots\dots (9)$$

$$\hat{X}_m = \frac{sG_{vl}}{s + G_{vl}} \hat{X}_m \dots\dots\dots (10)$$

where K_{tn} and M_n are refer to the nominal force coefficient and the nominal motor mass, respectively. G_{dis} is the cut-off frequency of the disturbance observer, G_{vl} is the cut-off frequency of the motor velocity estimation. To apply in the real controller, accurate measured data of velocity is required to provide high accurate force sensing of disturbance observer.

3.2 Load Disturbance Observer (LDOB) Because

of the advantages and unique features of disturbance observer, this approach has received much attention in sensorless force control system. However, instability and vibration of system can occur when using disturbance observer for the

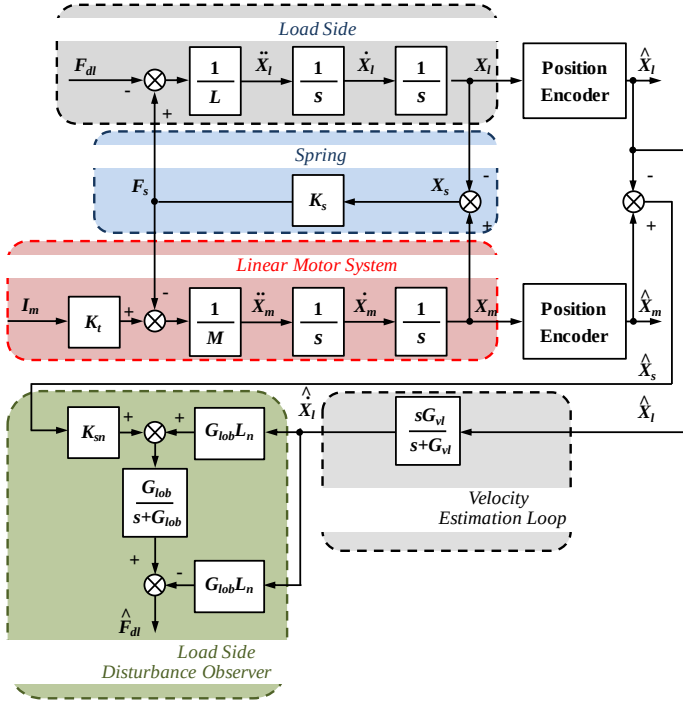


Fig. 4. Load side disturbance observer

two-mass system because of the presence of spring that degrade the overall performance.

To address these problems, a load disturbance observer (LDOB)⁽¹²⁾⁽¹³⁾, which is composed of the nominal spring coefficient K_{sn} , the nominal load mass L_n and the load-side encoder, has been proposed as follows,

$$F_{dl} = K_s X_s - L_n \ddot{X}_l \dots \dots \dots (11)$$

$$\hat{F}_{dl} = \left(\frac{G_{lob}}{s + G_{lob}} \left(K_{sn} (\hat{X}_l - \hat{X}_m) + G_{lob} L_n \hat{X}_l \right) - G_{lob} L_n \hat{X}_l \right) \dots \dots \dots (12)$$

$$\hat{X}_l = \frac{sG_{vl}}{s + G_{vl}} \hat{X}_l \dots \dots \dots (13)$$

where G_{vl} and G_{lob} are the cut-off frequency of the load velocity estimation and the LDOB, respectively. The structure of LDOB as described in this section can be applied to estimate the external force at the load side as shown in Fig. 4. The LDOB is proposed to estimate the external force on the load side. However, the exact parameters of the spring coefficient is difficult to obtain. Moreover, it can be assumed by a non-linear relationship.

3.3 Multi-Encoder Based Disturbance Observer (MEDOB) In our previous research, a novel multi-encoder-based disturbance observer (MEDOB) is proposed for estimating the external force at the load side of flexible robot as shown in Fig. 5. The method to estimate the external force at the load side is obtained from the equation (14), (15) and a simple first-order low-pass filter as follows,

$$F_{dl} = K_{tn} I_m - M_n \ddot{X}_m - L_n \ddot{X}_l \dots \dots \dots (14)$$

$$\hat{F}_{dl} = \left(\frac{G_{mob}}{s + G_{mob}} \left(K_{tn} I_m + G_{mob} M_n \hat{X}_m + G_{mob} L_n \hat{X}_l \right) - G_{mob} M_n \hat{X}_m - G_{mob} L_n \hat{X}_l \right) \dots \dots \dots (15)$$

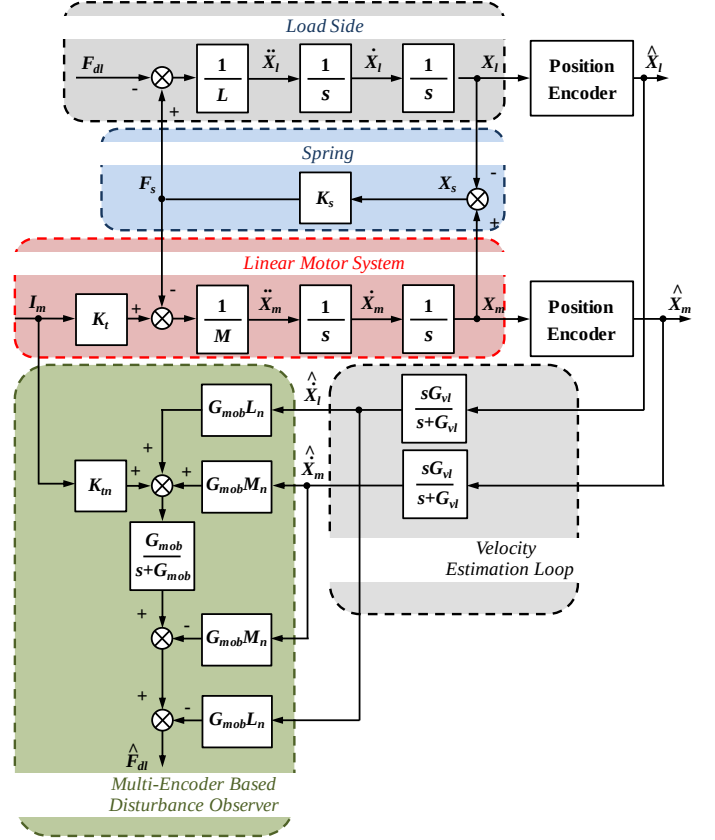


Fig. 5. Multi encoder based disturbance Observer

$$\dots \dots \dots -G_{mob} M_n \hat{X}_m - G_{mob} L_n \hat{X}_l \dots \dots \dots (15)$$

where G_{mob} is the cut-off frequency of the MEDOB. Compared to the other conventional ways such as state observer and LDOB, the proposed observer based on multi-encoder system offers the advantages of faster response, and high accuracy. By using the proposed observer, it is not necessary to estimate the nominal spring coefficient. It is simple to design and easily implemented into the system with the mechanical resonance. However, it is difficult to attach the encoder on the load side of the robot system.

3.4 Acceleration Sensor based Load Side Disturbance Observer (ALDOB) In this research, a new combined observer technique, named acceleration sensor based load side disturbance observer (ALDOB), has been proposed by using acceleration sensor on the load side and encoder on the motor side. The method to estimate the external force at the load side is obtained from the Kalman filter, disturbance observer and a simple first-order low-pass filter as follows,

$$\hat{F}_{dl} = \left(\frac{G_{mob}}{s + G_{mob}} \left(K_{tn} I_m + G_{mob} M_n \hat{X}_m \right) - G_{mob} M_n \hat{X}_m - L_n \hat{X}_l \right) \dots \dots \dots (16)$$

As shown in Fig. 6, the Kalman-filter is applied to compensate the unwanted white Gaussian noise of the acceleration signal. The process of the Kalman-filter consisting of

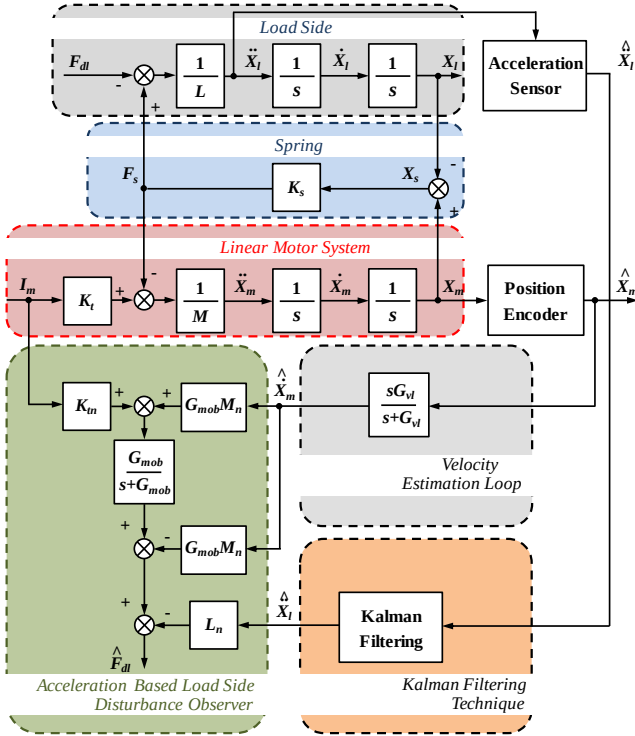


Fig.6. Acceleration sensor based load side disturbance observer.

the operation in two phases: prediction and update. The formulation of the Kalman filter equation is based on state space formulation. A discrete sensor dynamics model can be formulated in the state space form as

$$\mathbf{x}_{(k+1)} = \mathbf{A}_{(k)}\mathbf{x}_{(k)} + \mathbf{B}_{(k)}\mathbf{u}_{(k)} + \mathbf{w}_{(k)} \quad (17)$$

$$\mathbf{z}_{(k)} = \mathbf{C}_{(k)}\mathbf{x}_{(k)} + \mathbf{v}_{(k)} \quad (18)$$

where k represents the sampling instant, $\mathbf{x}_{(k)} \in \mathfrak{R}^n$ is the vector of states, $\mathbf{u}_{(k)} \in \mathfrak{R}^m$ is the vector of input variables, $\mathbf{A}_{(k)} \in \mathfrak{R}^{n \times n}$ and $\mathbf{B}_{(k)} \in \mathfrak{R}^{n \times m}$ are system matrices, $\mathbf{C}_{(k)} \in \mathfrak{R}^{s \times n}$ is the measurement matrix, $\mathbf{z}_{(k)} \in \mathfrak{R}^s$ is the vector of measured variables, $\mathbf{w}_{(k)}$ is the process noise and $\mathbf{v}_{(k)}$ represents the measurement which is corrupted by white Gaussian noise.

It is assumed that the covariance matrix of the process noise $\mathbf{Q}$, the covariance matrices of the measurement noise $\mathbf{R}$ and the cross-covariance matrix are as given below:

$$\mathbf{Q} = E\{\mathbf{w}\mathbf{w}^T\} > 0 \quad (19)$$

$$\mathbf{R} = E\{\mathbf{v}\mathbf{v}^T\} \geq 0 \quad (20)$$

$$E\{\mathbf{w}\mathbf{v}^T\} = 0 \quad (21)$$

The Kalman filter bandwidth and its susceptibility to measurement noise depends on its covariance matrix of process noise $\mathbf{Q}$ and the covariance matrix of measurement noise $\mathbf{R}$. These values are used to tune the accuracy and response of the observer, and the matrices $\mathbf{Q}$ and $\mathbf{R}$ can be determined by using the simulations for the testing of the measurement sensors. A compromise between the performance of observer and the compensation of acceleration signal noise can be

found.

The error covariance matrices $\mathbf{P}$ is the variance of the difference between the state and the measurements. The predicted equation which projects the current state estimate ahead in time are given by

$$\mathbf{x}_{(k|k-1)} = \mathbf{A}_{(k-1)}\mathbf{x}_{(k-1|k-1)} + \mathbf{B}_{(k-1)}\mathbf{u}_{(k-1)} \quad (22)$$

$$\mathbf{P}_{(k|k-1)} = \mathbf{A}_{(k-1)}\mathbf{P}_{(k-1|k-1)}\mathbf{A}_{(k-1)}^T + \mathbf{Q}_{(k-1)} \quad (23)$$

The Kalman filter gain matrix $\mathbf{M}$, that is based on the total uncertainty measurement of matrix $\mathbf{S}$ is computed by using the following equation

$$\mathbf{S}_{(k)} = \mathbf{C}_{(k)}\mathbf{P}_{(k|k-1)}\mathbf{C}_{(k)}^T + \mathbf{R}_{(k)} \quad (24)$$

$$\mathbf{M}_{(k)} = \mathbf{P}_{(k|k-1)}\mathbf{C}_{(k)}^T\mathbf{S}_{(k)}^{-1} \quad (25)$$

The estimated state vector and the error matrix are updated by an actual measurement $\bar{\mathbf{z}}_{(k)}$ of motion sensor at every sampling instant as follows

$$\mathbf{x}_{(k|k)} = \mathbf{x}_{(k|k-1)} + \mathbf{M}_{(k)}(\bar{\mathbf{z}}_{(k)} - \mathbf{C}_{(k)}\mathbf{x}_{(k|k-1)}) \quad (26)$$

$$\mathbf{P}_{(k|k)} = \mathbf{P}_{(k|k-1)} - \mathbf{M}_{(k)}\mathbf{S}_{(k)}\mathbf{M}_{(k)}^T \quad (27)$$

By using the acceleration sensor, the space requirement for sensor is very small. The mounting wax is used to mount a piezoelectric acceleration sensor on the end-effector of the robot. Thus, it is suitable for attaching sensor on the load-side of robot system.

4. Simulation and Results

The simulation was performed in order to evaluate the performance of each observer with respect to the parameter variation of the nominal spring coefficient K_{sn} . Fig. 7 shows the simulation result of the load-side external force without the variation of the spring coefficient. On the other hand, Fig. 8 and 9 show the estimated response of the load-side external force with varying of the range of the spring coefficient $\pm 5\%$, respectively.

External force was estimated through observer in which the output is then processed by a low-pass filter (500 rad/sec cutoff frequency). In the resonance ratio control^{(14) (15)}, the robot's task is commanded to control force with a given sinusoidal signal with an amplitude 10 N.

As can be seen in Fig. 8 and 9, a bad tracking result with phase shift and undesired vibration is obtained, since the parameter identification of spring was not correct in the LDOB. From the simulation result, the estimated load-side external force of MEDOB and ALDOB is well estimated and controlled to the command, although the parameter of the nominal spring coefficient is varied. Moreover, the proposed ALDOB observer was eliminated the need for the spring coefficient identification, and may also be used to achieve the precise load-side force estimation. Thus, these simulation outcomes could ensure high performance of the proposed observer.

5. Conclusion

The purpose of this research was to compare the load-side external force estimation under different types of observer such as LDOB, MEDOB and ALDOB. Based on our previous research, the MEDOB was very useful to implement in the

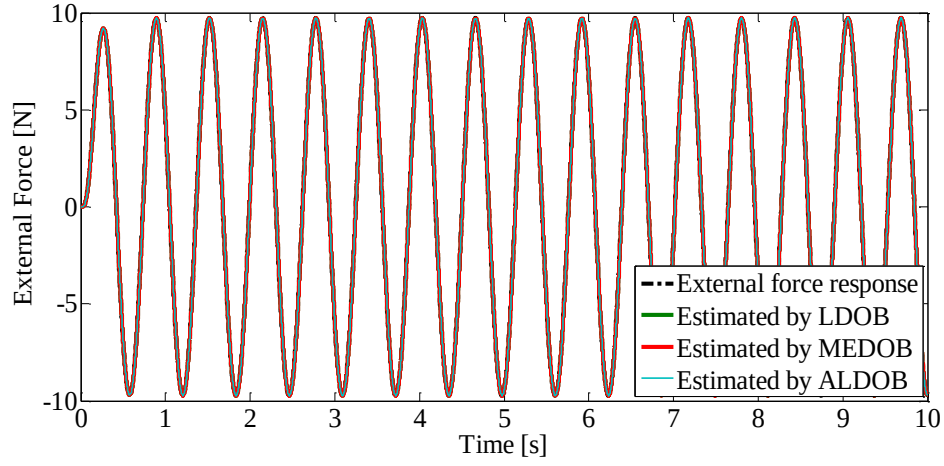


Fig. 7. Estimated response of the load-side external force.

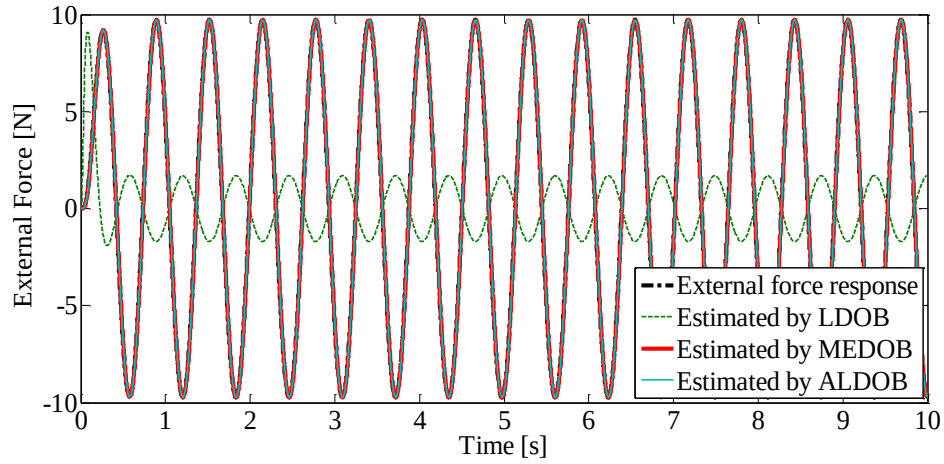


Fig. 8. Estimated response of the load-side external force with the K_s parameter variation +5%

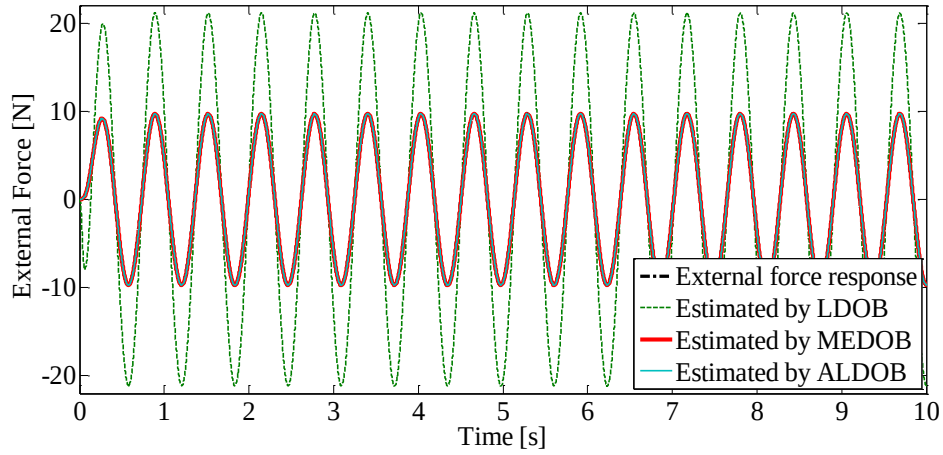


Fig. 9. Estimated response of the load-side external force with the K_s parameter variation -5%

system with mechanical resonance. However, it is difficult to attach the encoder on the load side of the robot system. In order to overcome this problem, the acceleration sensor with Kalman filter was used in order to increase the accuracy of the disturbance observer. The proposed ALDOB observer was eliminated the need for the spring coefficient identification, and may also be used to achieve the precise load-side force estimation. Moreover, the space requirement for sensor

attachment is very small. Thus, it is suitable for attaching sensor on the load-side of robot system. From the simulation results, the load-side external force estimation response was obtained without force sensor, since the ALDOB was implemented. Therefore, the proposed system can be applied practically for the robot system with mechanical resonance in industrial applications.

Acknowledgment

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Multi-Sensor Fusion Observer based Multilateral Control of Haptic Devices Without Force Sensor

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Abstract—Among all the sensor fusion approaches, Kalman filter is the most widely used technique for system state estimation. The Kalman filter has many uses, including applications in tracking objects, navigation, economics, computer vision and robot controlling. As an example application, it is suitable method for compensating noise measurements from sensor data input and also for sensor fusion. In this paper, a novel multilateral control based on observer technique has been proposed by using disturbance observer with Kalman filter, named Kalman-Filter based Disturbance Observer (KFDOB). Kalman-filter is designed to estimate velocity response and disturbance observer is used to estimate the action/reaction force of haptic devices. The design of multilateral control based on the Hadamard matrix is also presented. With such a robust sensorless force control scheme, high bandwidth of force sensing in multi-robot system may be achieved since acceleration sensor and optical encoder are used to estimate the external force information. Moreover, its measured noise is also significantly reduced. The experimental results are provided to illustrate the performance of the proposed algorithms.

I. INTRODUCTION

Multimedia technologies are used widely today because of their advantages to transform and record experience information in a purposeful way as shown in Fig. 1. Such vision or sound information is always transferred in only one way direction (Unilateral). On the other hand, to provide the sense of touch, haptic devices in master-slave configurations have been proposed. The concept of the two way communication (Bilateral) is made on the basis of the exchanged information between motors. Both of master and slave robots are controlled bilaterally with the same actions of force and motion movements.

Recently, an intelligent robot system has been used extensively for a wide range of applications. For example, the da Vinci surgical system [1] and ZEUS surgical system [2] have been introduced to perform the surgery effectively. However, force information is still not available to the surgeon. Such lack of the force sensing ability greatly limits effectiveness of the operations. In order to develop a new surgical robot system, an intelligent robot systems based on bilateral control or multilateral control are being built to support human operator.

The multilateral control system consists of master and slave robots assembled for the purpose of obtaining a same action of force and motion movements with desired performance. Generally, a force sensor has been widely applied to measure

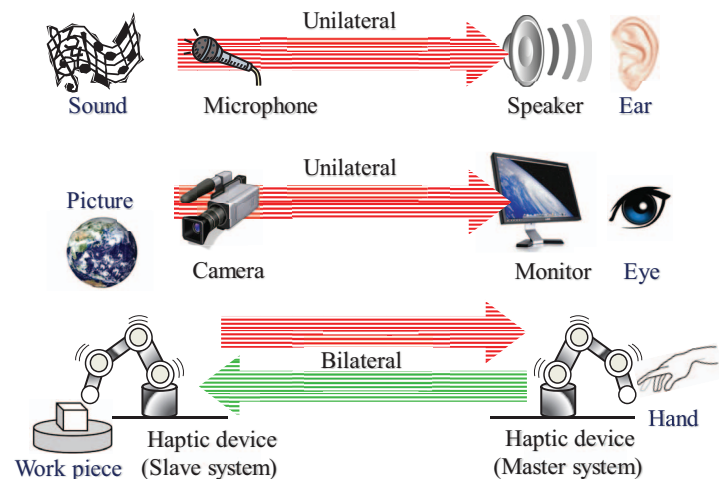


Fig. 1. Overview of Human Experience in A Digital World

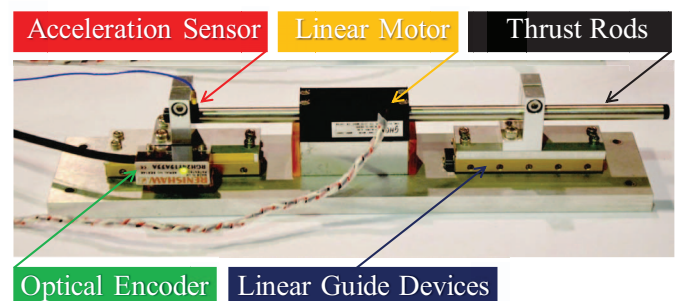


Fig. 2. Linear motor systems with multi-sensor fusion.

the external force information [3]. However, the problem of sensor noise, such as undesirable oscillations and instability, does not only degrade the performance at the slave side but also at the whole system. The sensor noise represents a major performance impairment that must be compensated.

To overcome this problem, a Kalman-Filter based Disturbance Observer has been proposed by using disturbance observer with Kalman filter to estimate an external force. Moreover, the KFDOB is applied in the multi robot system in order to confirm the effectiveness of the proposed method.

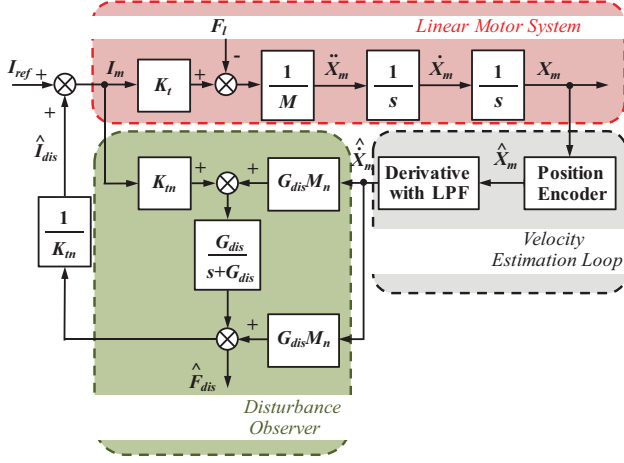


Fig. 3. Modeling of Linear Motor System with DOB.

II. MODEL OF THE HAPTIC DEVICE

In this research, an overview of the system hardware of haptic device is shown in Fig. 2. The experimental setup of haptic device consists of linear motors, linear guide devices, and motion sensors. The multi-sensor systems which consists of the optical linear encoder and acceleration sensor play a major role in control of the haptic device, by measuring the position and acceleration information. A non-contact optical linear encoder (RGH24 series; Renishaw) with high resolution grade of $0.1 \mu\text{m}$ is used to read the scale in order to convert the encoded position into a digital square wave signal.

The mounting wax is used to mounted a piezoelectric acceleration sensors (NP-3211; Ono Sokki Technology, Inc.) on the master and slave robots, and applied to converts mechanical vibrations into analog signals. It offers a sensitivity of 1.02 mV with 1 m/s^2 . The frequency response range is provided from 1Hz to 10kHz .

A model of the linear motor regulated under the ideal current source is shown in Fig. 3. From this figure, the dynamic equation of the linear motor is described by

$$M\ddot{X}_m = K_t I_m - (F_f + D\dot{X}_m + F_{ext} + \Delta M\ddot{X}_m + \Delta K_t I_m) \quad (1)$$

$$F_l = F_f + D\dot{X}_m + F_{ext} \quad (2)$$

where, M denotes the motor mass. X_m , $\dot{X}_m$ and $\ddot{X}_m$ denote the motor position, motor velocity and motor acceleration, respectively. K_t is the force coefficient, and I_m is motor current. The load force F_l is the summation of friction force F_f , viscous friction $D\dot{X}_m$ and external force F_{ext} . The equation of the load force is considered as (2). $\Delta M\ddot{X}_m$ is the variation torque due to changed mass, $\Delta K_t I_m$ is the force ripple due to space harmonics. The disturbance force on the motor side F_{dis} is defined as,

$$F_{dis} = F_f + D\dot{X}_m + F_{ext} + \Delta M\ddot{X}_m + \Delta K_t I_m \quad (3)$$

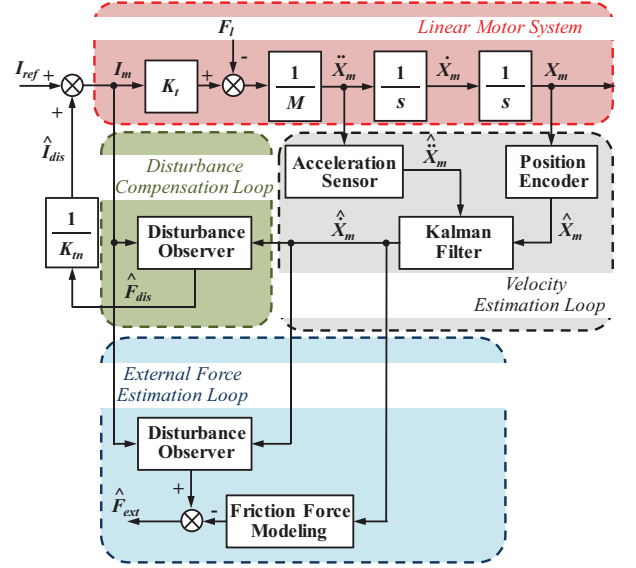


Fig. 4. Modeling of Linear Motor System with KFDOB.

III. MOTION SENSOR-BASED EXTERNAL FORCE ESTIMATION

A. Disturbance Observer (DOB)

The structure of disturbance observer [4], [5] is shown in Fig. 3. The method to estimate the velocity is obtained from a derivative with simple first-order of low-pass filter as follows,

$$\hat{F}_{dis} = \frac{G_{dis}}{S + G_{dis}} (K_{tn} I_m + G_{dis} M_n \hat{X}_m) - G_{dis} M_n \hat{X}_m \quad (4)$$

$$\hat{X}_m = \frac{SG_{ve}}{S + G_{ve}} \hat{X}_m \quad (5)$$

where G_{dis} is the cut-off frequency of the disturbance observer, G_{ve} is the cut-off frequency of the velocity estimation. The low-pass filter is used to design bandwidth of force estimation. In this research, it is assumed that the influence of the friction force is very small by using a small-size of linear motor; thus, the external forces have almost the same values of the disturbance force.

Because of the advantages and unique features of disturbance observer, this approach has received much attention in sensorless force control system. However, instability and vibration of system can occur when using disturbance observer for industrial applications because the presence of white Gaussian noise is deteriorated at any range of frequency. Since acceleration sensors is analog output, it have both continuous time noise and quantization noise terms.

B. Kalman-Filter Based Disturbance Observer (KFDOB)

To address these problems, KFDOB, which is composed of disturbance observer [4], [5] and Kalman filter [6], has been proposed. The formulation of the Kalman filter equation is based on state space formulation. A discrete sensor dynamics model can be formulated in the state space form as

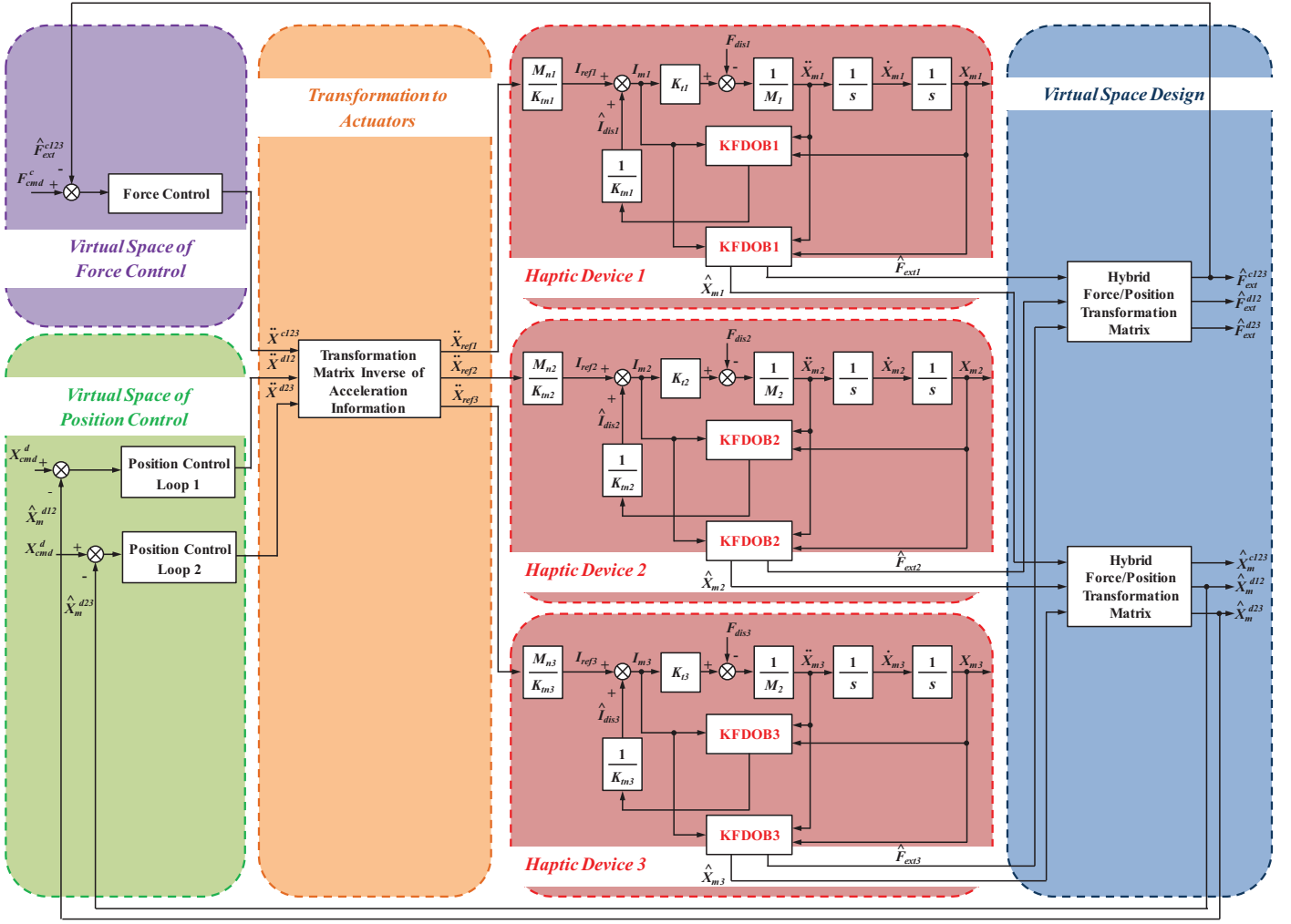


Fig. 5. Block diagram of the proposed multilateral control based on KFDOB.

$$\mathbf{x}_{(k+1)} = \mathbf{A}_{(k)}\mathbf{x}_{(k)} + \mathbf{B}_{(k)}\mathbf{u}_{(k)} + \mathbf{w}_{(k)} \quad (6)$$

$$\mathbf{z}_{(k)} = \mathbf{C}_{(k)}\mathbf{x}_{(k)} + \mathbf{v}_{(k)} \quad (7)$$

where k represents the sampling instant, $\mathbf{x}_{(k)} \in \mathfrak{R}^n$ is the vector of states, $\mathbf{u}_{(k)} \in \mathfrak{R}^m$ is the vector of input variables, $\mathbf{A}_{(k)} \in \mathfrak{R}^{n \times n}$ and $\mathbf{B}_{(k)} \in \mathfrak{R}^{n \times m}$ are system matrices, $\mathbf{C}_{(k)} \in \mathfrak{R}^{s \times n}$ is the measurement matrix, $\mathbf{z}_{(k)} \in \mathfrak{R}^s$ is the vector of measured variables, $\mathbf{w}_{(k)}$ is the process noise and $\mathbf{v}_{(k)}$ represents the measurement which is corrupted by white Gaussian noise. The system matrices can be formulated into the discrete state matrices as,

$$\mathbf{A} = \begin{bmatrix} 1 & T_k & \frac{T_k^2}{2} \\ 0 & 1 & T_k \\ 0 & 0 & 1 \end{bmatrix}, \mathbf{B} = \begin{bmatrix} 0 \\ \frac{K_{tn}T_k}{M_n} \\ 0 \end{bmatrix}, \quad (8)$$

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

It is assumed that the covariance matrix of the process noise $\mathbf{Q}$, the covariance matrices of the measurement noise $\mathbf{R}$ and

the cross-covariance matrix are as given below:

$$\mathbf{Q} = E\{\mathbf{w}\mathbf{w}^T\} > 0 \quad (9)$$

$$\mathbf{R} = E\{\mathbf{v}\mathbf{v}^T\} \geq 0 \quad (10)$$

$$E\{\mathbf{w}\mathbf{v}^T\} = 0 \quad (11)$$

The Kalman filter bandwidth and its susceptibility to measurement noise depends on its covariance matrix of process noise $\mathbf{Q}$ and the covariance matrix of measurement noise $\mathbf{R}$. These values are used to tune the accuracy and response of the observer, and the matrices $\mathbf{Q}$ and $\mathbf{R}$ can be determined by using the simulations for the testing of the measurement sensors. A compromise between the performance of observer and the compensation of acceleration signal noise can be found.

The error covariance matrices $\mathbf{P}$ is the variance of the difference between the state and the measurements. The predicted equation which projects the current state estimate ahead in

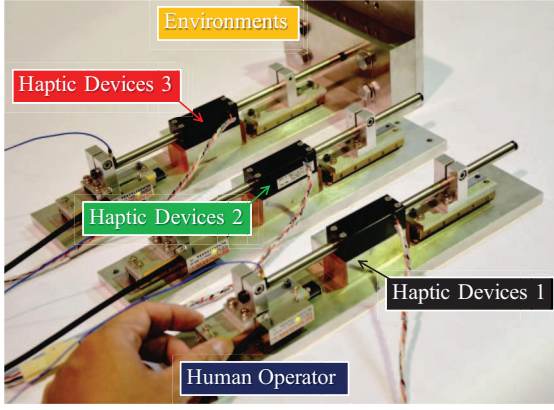


Fig. 6. Multi robot with multi-sensor fusion.

time are given by

$$\mathbf{x}_{(k|k-1)} = \mathbf{A}_{(k-1)}\mathbf{x}_{(k-1|k-1)} + \mathbf{B}_{(k-1)}\mathbf{u}_{(k-1)} \quad (12)$$

$$\mathbf{P}_{(k|k-1)} = \mathbf{A}_{(k-1)}\mathbf{P}_{(k-1|k-1)}\mathbf{A}_{(k-1)}^T + \mathbf{Q}_{(k-1)} \quad (13)$$

The Kalman filter gain matrix $\mathbf{M}$, that is based on the total uncertainty measurement of matrix $\mathbf{S}$ is computed by using the following equation

$$\mathbf{S}_{(k)} = \mathbf{C}_{(k)}\mathbf{P}_{(k|k-1)}\mathbf{C}_{(k)}^T + \mathbf{R}_{(k)} \quad (14)$$

$$\mathbf{M}_{(k)} = \mathbf{P}_{(k|k-1)}\mathbf{C}_{(k)}^T\mathbf{S}_{(k)}^{-1} \quad (15)$$

The estimated state vector and the error matrix are updated by an actual measurement $\bar{\mathbf{z}}_{(k)}$ of motion sensor at every sampling instant as follows

$$\mathbf{x}_{(k|k)} = \mathbf{x}_{(k|k-1)} + \mathbf{M}_{(k)}(\bar{\mathbf{z}}_{(k)} - \mathbf{C}_{(k)}\mathbf{x}_{(k|k-1)}) \quad (16)$$

$$\mathbf{P}_{(k|k)} = \mathbf{P}_{(k|k-1)} - \mathbf{M}_{(k)}\mathbf{S}_{(k)}\mathbf{M}_{(k)}^T \quad (17)$$

IV. CONTROLLER DESIGN FOR MULTILATERAL CONTROL

This paper also deals with the construction of multilateral control with the use of modal space design provided by the calculation of Hadamard matrix [5], [7] as shown in Fig. 5. The complexities that control of master-slave robots present are synchronization in terms of movements and force. Master and slave robot must be controlled similarly. Thus, the target of the ideal multilateral control is to minimize the difference between the force response in the master side $\hat{F}_{ext1}$ and slave side $\hat{F}_{ext2}, \hat{F}_{ext3}$ as follows,

$$\hat{F}_{ext1} + \hat{F}_{ext2} + \hat{F}_{ext3} = 0 \quad (18)$$

Moreover, the position tracking of the master robot $\hat{X}_{m1}$ and slave robot $\hat{X}_{m2}, \hat{X}_{m3}$ should be similar, as follows,

$$\hat{X}_{m1} = \hat{X}_{m2} = \hat{X}_{m3} \quad (19)$$

$$\hat{X}_{m1} - \hat{X}_{m2} = 0 \quad (20)$$

$$\hat{X}_{m2} - \hat{X}_{m3} = 0 \quad (21)$$

Two control modes, namely the common mode and differential mode, are implemented and applied to control both the position and force. The underscript number 1 2 and 3

identify the master robot 1, slave robot 2, and slave robot 3 respectively. In order to obtain information for the modal space design, the force estimation from the KFDOB at the master side, $\hat{F}_{ext1}$, and the KFDOB at the slave side, $\hat{F}_{ext2}, \hat{F}_{ext3}$, are transformed into the virtual force in the common mode, $\hat{F}_{ext}^{c123}$, and the differential mode, $\hat{F}_{ext}^{d12}, \hat{F}_{ext}^{d23}$, by using the Hybrid force/position transformation matrix based on the third order of Hadamard matrix, $\mathbf{H}_3$. On the other hand, the position signals from the KFDOB at the master side, $\hat{X}_{m1}$, and the slave side, $\hat{X}_{m2}, \hat{X}_{m3}$ are also transformed into the virtual position in the common mode, $\hat{X}_m^{c123}$, and the differential mode, $\hat{X}_m^{d12}, \hat{X}_m^{d23}$, by using the $\mathbf{H}_3$. The virtual position of each mode is represented as follows:

$$\begin{bmatrix} \hat{F}_{ext}^{c123} \\ \hat{F}_{ext}^{d12} \\ \hat{F}_{ext}^{d23} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} \hat{F}_{ext1} \\ \hat{F}_{ext2} \\ \hat{F}_{ext3} \end{bmatrix} \quad (22)$$

$$\begin{bmatrix} \hat{X}_m^{c123} \\ \hat{X}_m^{d12} \\ \hat{X}_m^{d23} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} \hat{X}_{m1} \\ \hat{X}_{m2} \\ \hat{X}_{m3} \end{bmatrix} \quad (23)$$

The force control in the common mode can be separately analyzed as the proportional controller as shown in the following equation,

$$\ddot{X}^{c123} = (F_{cmd}^c - \hat{F}_{ext}^{c123})K_f \quad (24)$$

where F_{cmd}^c is the force command and K_f is the proportional gain of force control.

On the other hand, the position control in the differential mode can be analyzed as the proportional-derivative (PD) controller. The modal space designed of each mode is controlled in the acceleration dimension as follows,

$$\ddot{X}^{d12} = (X_{cmd}^d - \hat{X}_m^{d12})(K_{p12} + sK_{d12}) \quad (25)$$

$$\ddot{X}^{d23} = (X_{cmd}^d - \hat{X}_m^{d23})(K_{p23} + sK_{d23}) \quad (26)$$

where X_{cmd}^d is the position command. According to the targets of the bilateral control, both force and position command were set as zero. K_{p12}, K_{p23} and K_{d12}, K_{d23} are the proportional gain and the derivative gain of position control, respectively.

In order to transform into the master robot and slave robot, the transformation matrix inverse matrix $\mathbf{H}_3^{-1}$ is applied. The transformation of acceleration control signals from modal space design to the real space in the master robot $\ddot{X}_{ref1}$ and slave robot $\ddot{X}_{ref2}, \ddot{X}_{ref3}$ are calculated as follows,

$$\begin{bmatrix} \ddot{X}_{ref1} \\ \ddot{X}_{ref2} \\ \ddot{X}_{ref3} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 2 & 1 \\ 1 & -1 & 1 \\ 1 & -1 & -2 \end{bmatrix} \begin{bmatrix} \ddot{X}^{c123} \\ \ddot{X}^{d12} \\ \ddot{X}^{d23} \end{bmatrix} \quad (27)$$

where $\ddot{X}^{c123}$ is the acceleration control signal in the common mode. In the differential mode, $\ddot{X}^{d12}$ is the acceleration control signal between the first and the second haptic devices and $\ddot{X}^{d23}$ is the acceleration control signal between the

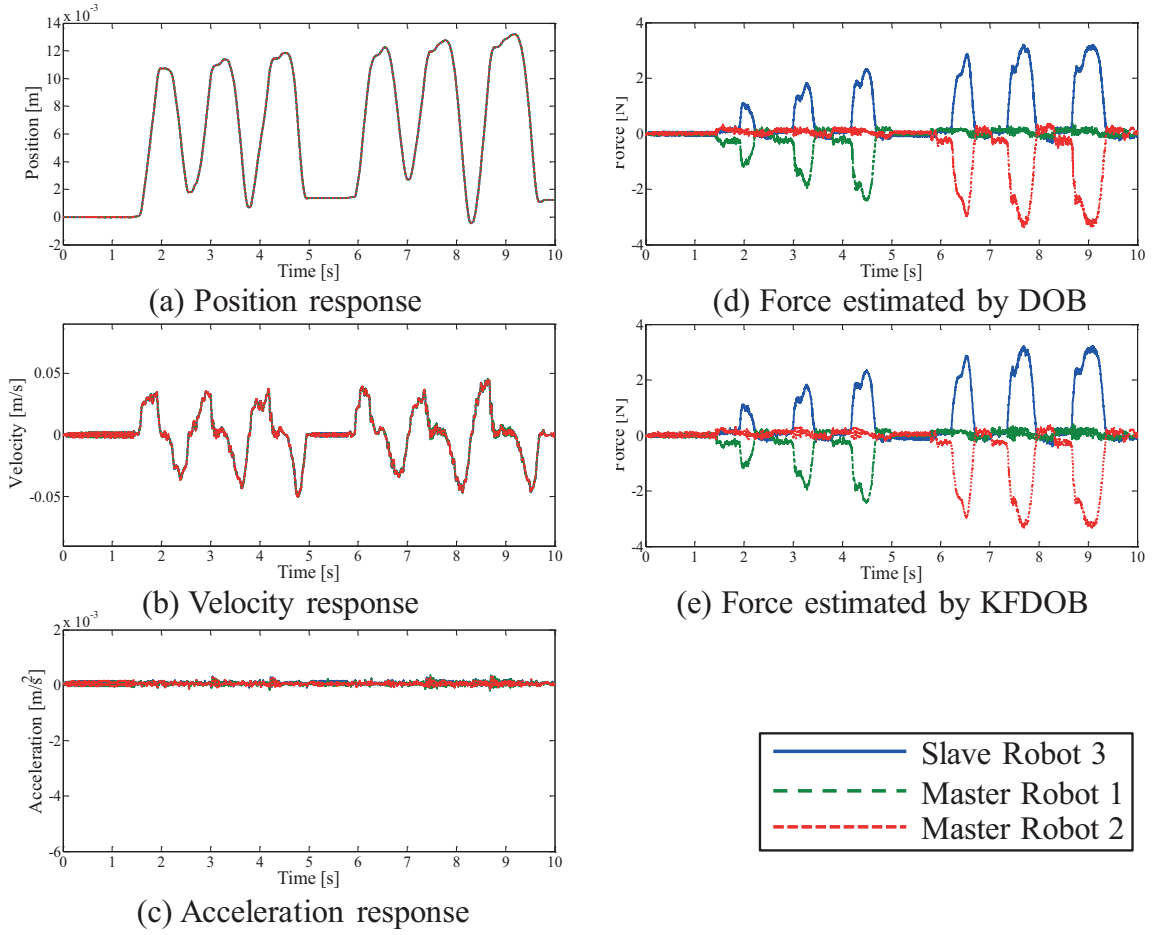


Fig. 7. Experimental results of soft environment (a sponge).

second and the third haptic device. A robust control system is attained by applying the KFDOB. In addition, an acceleration control system is attained on robust interaction force control. Therefore, it is able to design the sensorless force control and position control in acceleration dimension independently by realizing the system based on common mode and differential mode.

V. EXPERIMENTAL RESULTS

The experimental setup of multilateral control consists of three set of haptic devices as shown in Fig. 6. The master-slave robots are controlled by a PC using RT-Linux with a sampling time of $100 \mu\text{s}$. The computer is equipped with analog output board, analog input board, and encoder-pulse counter board. All of the data from sensors as well as the controllers are written in the C language. The experiments were performed to evaluate the performance of the proposed approach. The slave robot was commanded by the human operator at the master side to make contact with, and apply force to the soft environment, which is a sponge, was used. User operates haptic device 1 (Master robot) at 1.5s and operates haptic device 2 at 6.0 s. The period between 5.0s and 6.0s is a rest/transition period where no motion is produced. The haptic

device 3 (Slave robot) is controlled to move and contact a soft sponge by the end-effectors of the robot. The force and movement responses at both master and slave sides are shown in Fig.7. Fig. 7(a), (b), and (c) show the experimental results of the value of position, velocity, and acceleration response, respectively. Figure 7(e) shows the results of the proposed method where the action/reaction response at the master and slave side were estimated by the KFDOB. The force response at the slave side sensed by the KFDOB is in opposite directions with respect to the force response at the master side sensed by the DOB. From the experimental results, a high performance of the position control and force control can be achieved by applying the proposed KFDOB. In the second experiments, the high stiffness environment, which is an aluminium block, was used. From the experimental results of Fig. 8(d), the DOB did not exhibit perfect transmission of the contact information to the master side, especially at the onset of the contact phase. When the impact force is performed beyond the frequency bandwidth of the DOB, which is based on only optical linear encoder, the force signals are distorted due to the cut-off frequency of the low-pass filter. By using the proposed method, the reaction response of master side can be tracked almost identically over the action response of slave sides. After the

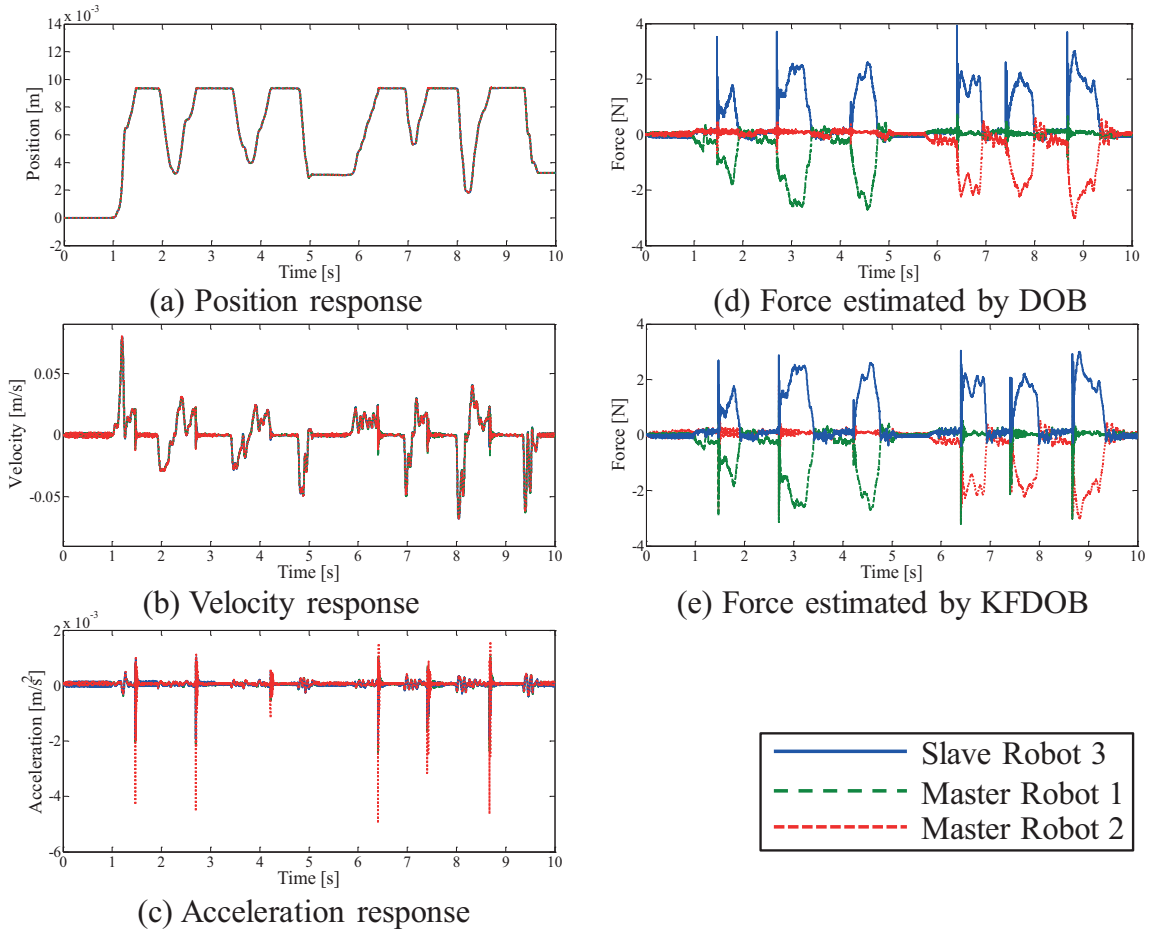


Fig. 8. Experimental results of hard environment (an aluminium block).

slave robot is moved to contact the hard environment, the force feedback is transmitted to the master robot with very fast response and high bandwidth sensation.

VI. CONCLUSION

This paper presented a comparative study of force estimation of the DOB and KFDOB for multilateral control of a small-sized linear motor with different types of motion sensors. Kalman-filter techniques were employed to enhance the performance of velocity and force estimation. Thus, these design techniques overcame limitation in the design of disturbance observer. Moreover, feedback of disturbance compensation loop can also be used to improve the robustness of the multilateral control system. The modal space design techniques is based upon realizing the Newton's law of action and reaction in order to achieve high transparency of multilateral control. It is clear that high transparency and good perception of the environmental stiffness with multi-robot system can be achieve successfully. It is not necessary to modify parameter gains according to the stiffness of environment. The system has high robustness against the parameter variations, disturbance effects, and unknown environments.

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Robot System for Rehabilitation of Wrist Using Bilateral Control Base on Disturbance Observer

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Abstract—In recent years, rehabilitation technology has been widely researched in order to help stroke patient recovery. In this research, a new wrist robot assistive system has been proposed by using bilateral control system based on disturbance observer. The proposed wrist robot assistive system consists of master and slave robot. The bilateral control supplies interaction force feedback information of rehabilitation training through a master robot of the physician. On the other hand, a slave robot is applied to interact with the patient. This paper also deals with the construction of disturbance observer to estimate external force between patient and physician. From the results, it is confirmed that the disturbance observer can be used instead of the real force sensor. By using the proposed bilateral controller, it is possible to provide a high transparency and good perception interaction force of assisting rehabilitation training. The simulation results are provided to illustrate the performance of the proposed algorithms.

Keywords: wrist, cuff, rehabilitation robot, disturbance observer

I. INTRODUCTION

In recent years, the rehabilitation robotics can be considered a challenge research to increase opportunities for facilitating access between physiotherapist and patient. One of interesting field to be applied for rehabilitation treatment is the technology of bilateral control system used in master – slave robot control. We were looking on scarcity in rehabilitation robot technology, an experience of rehabilitation robot and amount of physiotherapist in each region or country. Focus on the experience; patients have a different age or point of disorder then require different treatment/techniques of physical therapy each. So we had the idea to make both unite to achieve increasingly high performance is the idea to use robots as an intermediary between doctors and patients.

A robot for wrist rehabilitation is as assistive technology that focused on development of robot as a supporting tool for patients. The robot has diver mechanic design for a different target such as MIT-MANUS [3-5], mainly focused on the shoulder, elbow and wrist. Or Wrist Gimbal [6], focused on the forearm and wrist, develop with three degree of freedom exoskeleton. On the control method has developed on force control with load sensor or force sensor as well. This work proposes on disturbance observer to control system without force sensors and solve of noise and bandwidth range of sensor.

In order of bilateral control, the method to control the robot on master-slave system has been proposed on many task applications, which controlled bilaterally with the same

position movement and action force [1]. For example, haptic system of robot arm is the master side that used by user. The slave side has contracted on the unknown environment, robot have feedback of force and movement to master side, which is an ideal of bilateral control. That had been apply on multilateral control, main control robot more than two system [2]

In this paper, we introduce the acceleration control and the disturbance observer in Section II. The design of bilateral control present in Section III. Result with discussion are shown in Section IV and the conclusions in Section V. an application of haptic system on wrist rehabilitation by using bilateral control based on disturbance observer. Our main design goal has been developed of a robust, safe device with a telemedicine for wrist rehabilitation, starter on the two active DOF of wrist correspond to flexion/extension and radial deviation/ulnar deviation. The model of robot system focused on wrist movement only, show in Fig. 1.

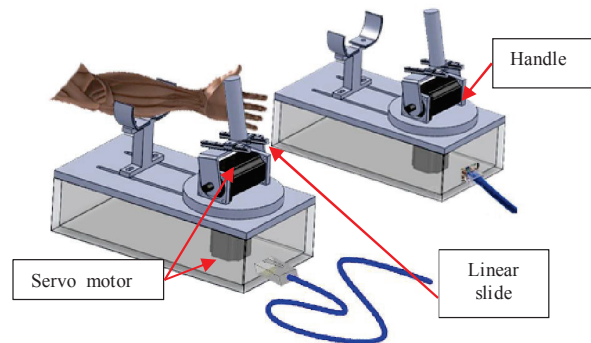


Fig.1. Model of robot rehabilitation for wrist.

II. ROBUST ACCELERATION CONTROL SYSTEM

A. Acceleration control

The model of an electric motor is an ideal of current source control. where τ_l , I_M , $\ddot{\theta}_M$ are external force, motor current and acceleration of motor, respectively. It can generated force by dynamical equation of the motor and represented by multiply current I_M . The dynamic equation of an electric motor is shown by equation (1):

$$J\ddot{\theta}_M = I_M K_t - \tau_l \quad (1)$$

Disturbance observer

$$\tau_{dis} = (J - J_n)\ddot{\theta}_M + (K_{tn} - K_t)I_M + \tau_f + D\dot{\theta}_M + \tau_{ext} \quad (2)$$

In the equation (2), a low pass filter is applied to design bandwidth of force estimation to avoid the effect from noise. By setting a low bandwidth for the observer, the smoothing sets of force data with low noise are obtained. However, both stability and response of the force control system are damaged.

$$\hat{\tau}_{dis} = \frac{G_{dis}}{S + G_{dis}} \tau_{dis} \quad (3)$$

III. BILATERAL CONTROL

$$\theta_M = \theta_S \quad (4)$$
$$\tau_{Ml} + \tau_{Sl} = 0 \quad (5)$$
$$\begin{bmatrix} \hat{\tau}_{ext}^c \\ \hat{\tau}_{ext}^d \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \hat{\tau}_{Mldis} \\ \hat{\tau}_{Sldis} \end{bmatrix} = H_2 \begin{bmatrix} \hat{\tau}_{Mldis} \\ \hat{\tau}_{Sldis} \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} \hat{\theta}_{ext}^c \\ \hat{\theta}_{ext}^d \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \theta_M \\ \theta_S \end{bmatrix} = H_2 \begin{bmatrix} \theta_M \\ \theta_S \end{bmatrix} \quad (7)$$

$$\ddot{\theta}_{ref}^c = (\tau_{cmd}^c - \hat{\tau}_{ext}^c)P_f \quad (8)$$

$$\ddot{\theta}_{ref}^d = (\theta_{cmd}^d - \hat{\theta}_{ext}^d)(P_p + D_p) \quad (9)$$

$$\begin{bmatrix} \ddot{\theta}_{Mref} \\ \ddot{\theta}_{Sref} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \ddot{\theta}_{ref}^c \\ \ddot{\theta}_{ref}^d \end{bmatrix} = H_2^{-1} \begin{bmatrix} \ddot{\theta}_{ref}^c \\ \ddot{\theta}_{ref}^d \end{bmatrix} \quad (10)$$

Fig. 4 shows a design of bilateral system by using the disturbance observer in this simulation follow equations (4) – (10). Fig. 3 shows an overview of robot system designed by using two bilateral control loops for two joints of the robot, joint#1 and joint#2, identified by superscript number 1 and 2, are assume to have minimum of dimension between joint#1 and joint#2.

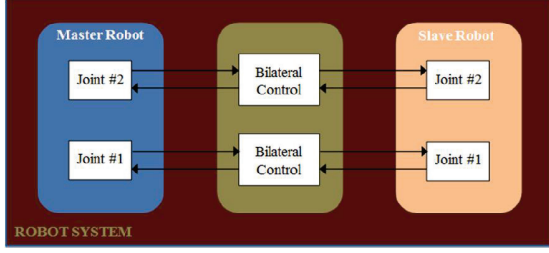


Fig. 3. Block diagram of robot system overview.

TABLE I
PARAMETER USED

Controller parameters	Symbol	Value	Unit
Nominal motor mass	J_n	5.7	Kgm^2
Nominal force coefficient	K_{tn}	4.46	Nm/A
Gain of disturbance observer	G_{dis}	600	rad/s

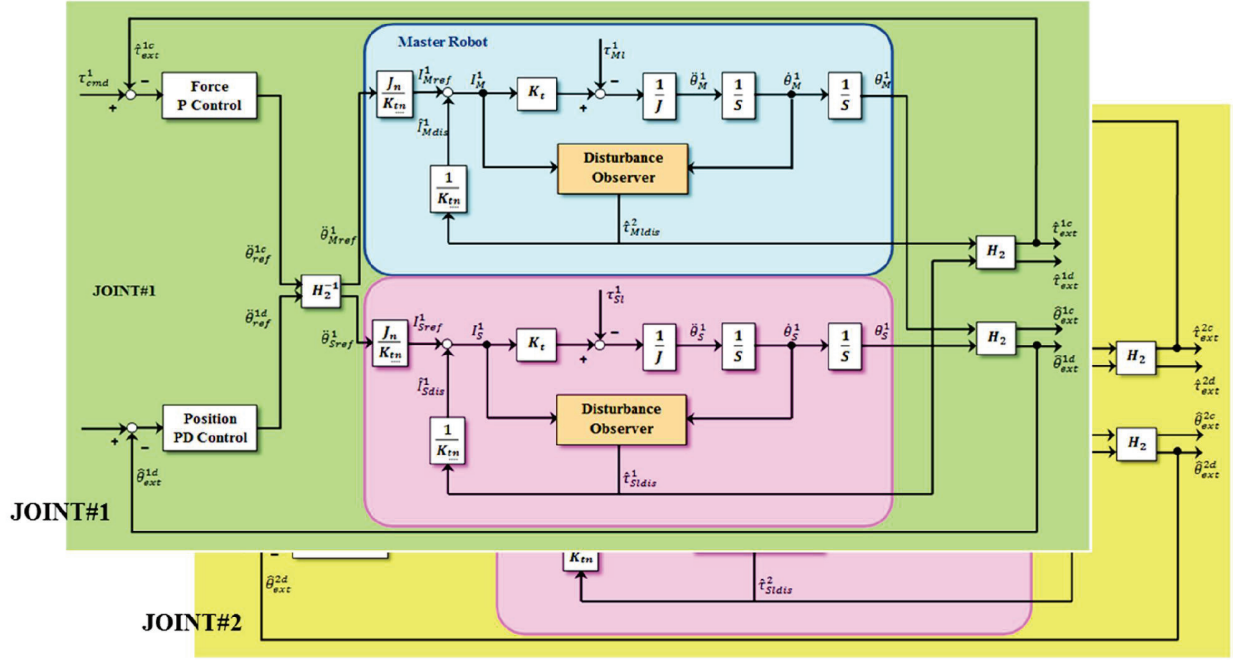


Fig. 4. Block diagram of the propose bilateral control.

IV. RESULT

A. supposing input

Fig. 5 shows about force input. Generate from a basic wrist movement on the master side, where the first motor moves on Flexion and Extension, the second motor move on radial deviation and ulnar deviation respective. There are three movement combination , first active only motor one moving left and right, second active only motor two moving up and down, third both active moving like a donut. External force assumes to be human force by multiply constant gain with position and velocity.

B. Result

Result from MATLAB simulation of wrist rehabilitation root shown in five parts of system result about force and position.

Fig. 7 shows about different position value of robot on master side and slave side with disturbance feedforward loop (show on below side) and without disturbance feedforward loop (show on upper side).

Fig. 8 shows position response between two joint of robot by upper represent joint#1 and another represent joint#2. It shows position response in the same between master side and slave side.

Fig. 9 shows force result of robot on master and slave side by upper represent joint#1 and lower represent joint#2. It shown force results have inverse between master and slave side. Follow a Newton law "Action = Reaction".

An ideal of bilateral control that is the difference between the positions of master and slave side should be zero, it show on minimize of different like same as zero and sum of force between master and slave should be zero, represent in Fig. 10.

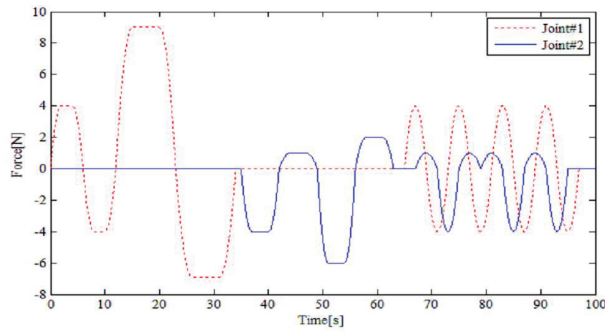


Fig. 5. Force suppling input.

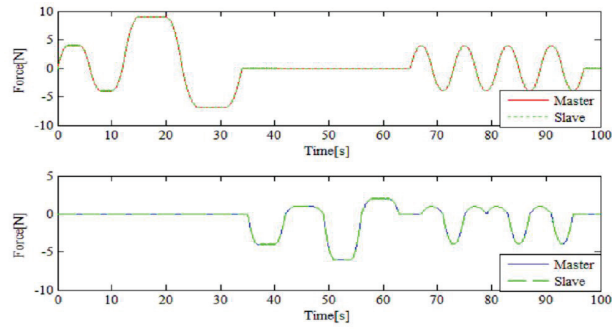


Fig. 6. Force estimate by disturbance observer.

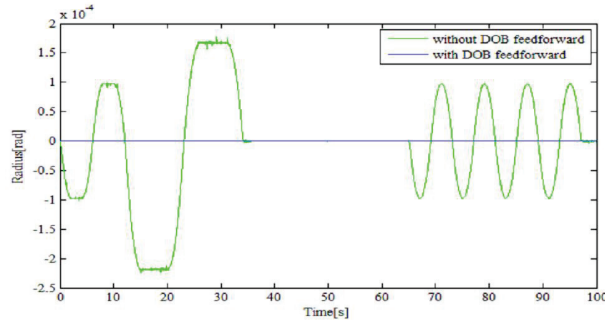


Fig. 7. Error of position, comparison with/without disturbance loop

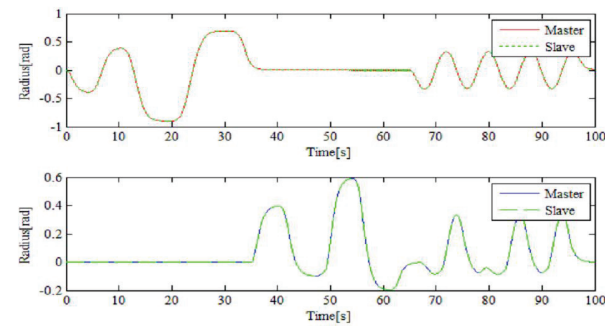


Fig 8. Position response at master and slave of two joint of robot.

Acknowledgement

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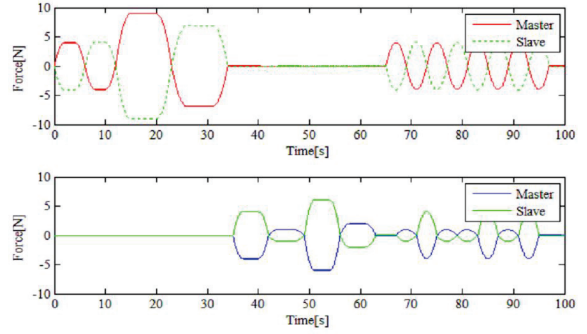


Fig. 9. Force response at master and slave of two joint of robot.

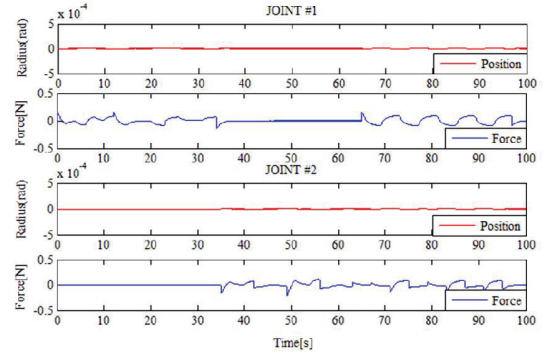


Fig. 10. Different of position between master/slave and summary of force between master and slave.

V. CONCLUSIONS

In this study, we have presented detail of design method to control the wrist rehabilitation robot on two DOF by using bilateral control base on disturbance observer. Bilateral control system can control position and force, which an ideal of same position and action-reaction force. Disturbance observer can estimate external force without force sensor. The simulation result confirms the force control loop implemented as feedforward is stable control for a disturbance force compensation. Future work will be focused on doing experiment with a test-rig design for up to 3 DOF of wrist.

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An Improvement of Multilateral Control Performance of A Teleoperated Robot Using Kalman-Filter-Based State Observer

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Abstract— This research focuses on the high bandwidth force sensation for haptic transmission with low noise disturbance. A Kalman-filter-based state observer (KFSO) has been designed to estimate action/reaction force of the master and slave robots. The stable control loop can be obtained when a KFSO is implemented as the feedforward control for a disturbance torque compensation loop. Moreover, this paper also deals with the construction of multilateral control with the use of modal space design provided by the calculation of Hadamard matrix. With such a robust force control scheme, significant high bandwidth haptic sensing in a multilateral control can be achieved. It is possible to provide high transparency and good perception of the environmental stiffness with multi-robot system. Under noisy conditions, a high performance of the position control and force control can be achieved by applying the Kalman filtering. The simulation results are provided to illustrate the performance of the proposed algorithms.

I. INTRODUCTION

Multimedia technologies are used widely today because of their advantages to transform and record experience information in a purposeful way. As shown in Fig. 1, a microphone is used for converting and recording sound into an electrical signal. To adequately reproduce sound waves, an electrical signal must be reconverted to analog form during playback before it is applied to a speaker. Motion picture information is obtained by a video camera, and a television or monitor make it possible to transmit visual sensation by broadcasting channel. However, such information is always transferred in only one way direction (Unilateral).

To provide the sense of touch, haptic devices in master-slave configurations have been proposed. The concept of the two way communication (Bilateral) is made on the basis of the exchanged information between motors. The bilateral control supplies force feedback information to the human operator through a master robot. On the other hand, a slave robot applied to interact with unknown environments. Both of master and slave robots are controlled bilaterally with the same actions of force and motion movements.

There has been a lot of discussion of how to improve the performance of bilateral control. Because of the advantages and unique features of disturbance observer [?], this approach has received much attention in sensorless force control system.

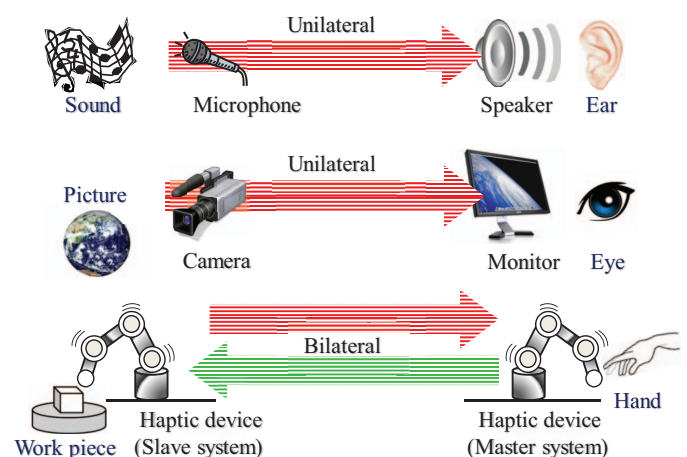


Fig. 1. Overview of Human Experience in A Digital World

Many practical application systems have been confirmed that the disturbance observer can be used instead of the real force sensor [?]. However, instability and vibration of system can occur when using disturbance observer for industrial applications because the presence of white Gaussian noise is deteriorated at any range of frequency. In this research, the proposed disturbance observer based on the Kalman filter [?], named Kalman-Filter-Based State Observer (KFSO), is designed to estimate the action/reaction force of each robot. The main objective of this research is also to find the solution for how we could design the multilateral controller as shown in Fig.2. As the proposed algorithm transforms and controls an acceleration information according to the Newtons law of action and reaction, this feature may make it very useful to control multi-robot with high transparency of force sensation.

II. MODEL OF THE HAPTIC DEVICE

A model of the linear motor regulated under the ideal current source is shown in Fig. 3. From this figure, the dynamic

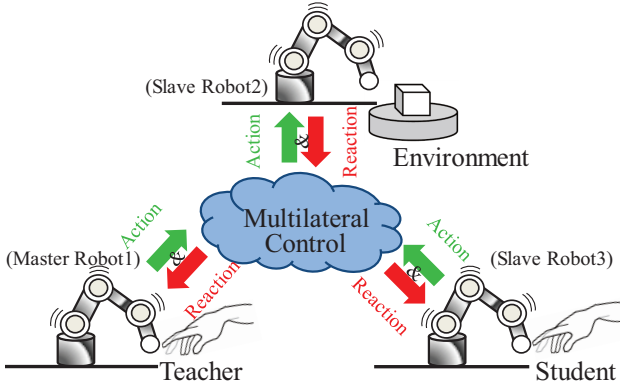


Fig. 2. Multilateral control of multi-robot system

equation of the linear motor is described by

$$M\ddot{X}_m = K_t I_m - \left(F_f + D\dot{X}_m + F_{ext} + \Delta M\ddot{X}_m + \Delta K_t I_m \right) \quad (1)$$

$$F_{dis} = F_f + D\dot{X}_m + F_{ext} \quad (2)$$

where, M denotes the motor mass. X_m , $\dot{X}_m$ and $\ddot{X}_m$ denote the motor position, motor velocity and motor acceleration, respectively. K_t is the force coefficient, and I_m is motor current. The load force F_l is the summation of friction force F_f , viscous friction $D\dot{X}_m$ and external force F_{ext} . The equation of the load force is considered as (2). $\Delta M\ddot{X}_m$ is the variation torque due to changed mass, $\Delta K_t I_m$ is the force ripple due to space harmonics. The disturbance force on the motor side F_{dis} is defined as,

$$F_{dis} = F_f + D\dot{X}_m + F_{ext} + \Delta M\ddot{X}_m + \Delta K_t I_m \quad (3)$$

III. ESTIMATION OF ACTION/REACTION FORCE USING KALMAN-FILTER-BASED STATE OBSERVER (KFSO)

In this research, the action/reaction forces and motions of the master-slave robots can be estimated with the use of Kalman-Filter-Based State Observer (KFSO). In order to extract accurate of forces on the robot, the nominal force coefficient and the nominal motor mass needs to be modeled and used in the observer. The model of the robot system can be formulated into the discrete state matrices as,

$$\mathbf{A} = \begin{bmatrix} 1 & T_k & -\frac{T_k^2}{2M_n} \\ 0 & 1 & -\frac{T_k}{M_n} \\ 0 & 0 & 1 \end{bmatrix}, \mathbf{B} = \begin{bmatrix} 0 \\ \frac{K_{tn}T_k}{M_n} \\ 0 \end{bmatrix}, \quad (4)$$

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$$

where T_k is a sampling time of the controller. The vector of states consists of motor position, motor velocity, and the external force. Motor current and position information are the reference inputs of the KFSO whereas the estimation of disturbance force $\hat{F}_{dis}$ is the output as shown in Fig. 3. where we can think of $\frac{1}{K_{tn}}$ as a transfer function transforming disturbance force to current. The estimation of disturbance force is used to compensate for unwanted disturbance that

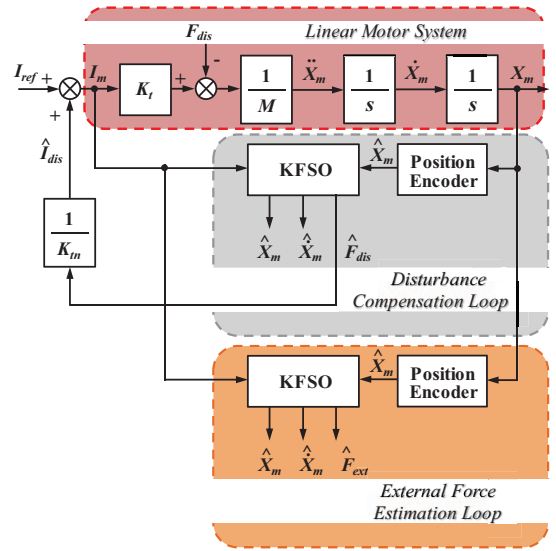


Fig. 3. Modeling of Linear Motor System with KFSO.

enter a system. Therefore, the system can be designed to follow the command input with small error.

A discrete sensor dynamics model can be formulated in the state space form as

$$\mathbf{x}_{(k+1)} = \mathbf{A}_{(k)}\mathbf{x}_{(k)} + \mathbf{B}_{(k)}\mathbf{u}_{(k)} + \mathbf{w}_{(k)} \quad (5)$$

$$\mathbf{z}_{(k)} = \mathbf{C}_{(k)}\mathbf{x}_{(k)} + \mathbf{v}_{(k)} \quad (6)$$

where k represents the sampling instant, $\mathbf{x}_{(k)} \in \mathfrak{R}^n$ is the vector of states, $\mathbf{u}_{(k)} \in \mathfrak{R}^m$ is the vector of input variables, $\mathbf{A}_{(k)} \in \mathfrak{R}^{n \times n}$ and $\mathbf{B}_{(k)} \in \mathfrak{R}^{n \times m}$ are system matrices, $\mathbf{C}_{(k)} \in \mathfrak{R}^{s \times n}$ is the measurement matrix, $\mathbf{z}_{(k)} \in \mathfrak{R}^s$ is the vector of measured variables, $\mathbf{w}_{(k)}$ is the process noise and $\mathbf{v}_{(k)}$ represents the measurement which is corrupted by white Gaussian noise.

The error covariance matrices $\mathbf{P}$ is the variance of the difference between the state and the measurements. The predicted equation which projects the current state estimate ahead in time are given by

$$\mathbf{x}_{(k|k-1)} = \mathbf{A}_{(k-1)}\mathbf{x}_{(k-1|k-1)} + \mathbf{B}_{(k-1)}\mathbf{u}_{(k-1)} \quad (7)$$

$$\mathbf{P}_{(k|k-1)} = \mathbf{A}_{(k-1)}\mathbf{P}_{(k-1|k-1)}\mathbf{A}_{(k-1)}^T + \mathbf{Q}_{(k-1)} \quad (8)$$

The Kalman filter gain matrix $\mathbf{M}$, that is based on the total uncertainty measurement of matrix $\mathbf{S}$ is computed by using the following equation

$$\mathbf{S}_{(k)} = \mathbf{C}_{(k)}\mathbf{P}_{(k|k-1)}\mathbf{C}_{(k)}^T + \mathbf{R}_{(k)} \quad (9)$$

$$\mathbf{M}_{(k)} = \mathbf{P}_{(k|k-1)}\mathbf{C}_{(k)}^T\mathbf{S}_{(k)}^{-1} \quad (10)$$

The estimated state vector and the error matrix are updated by an actual measurement $\bar{\mathbf{z}}_{(k)}$ of motion sensor at every sampling instant as follows

$$\mathbf{x}_{(k|k)} = \mathbf{x}_{(k|k-1)} + \mathbf{M}_{(k)}(\bar{\mathbf{z}}_{(k)} - \mathbf{C}_{(k)}\mathbf{x}_{(k|k-1)}) \quad (11)$$

$$\mathbf{P}_{(k|k)} = \mathbf{P}_{(k|k-1)} - \mathbf{M}_{(k)}\mathbf{S}_{(k)}\mathbf{M}_{(k)}^T \quad (12)$$

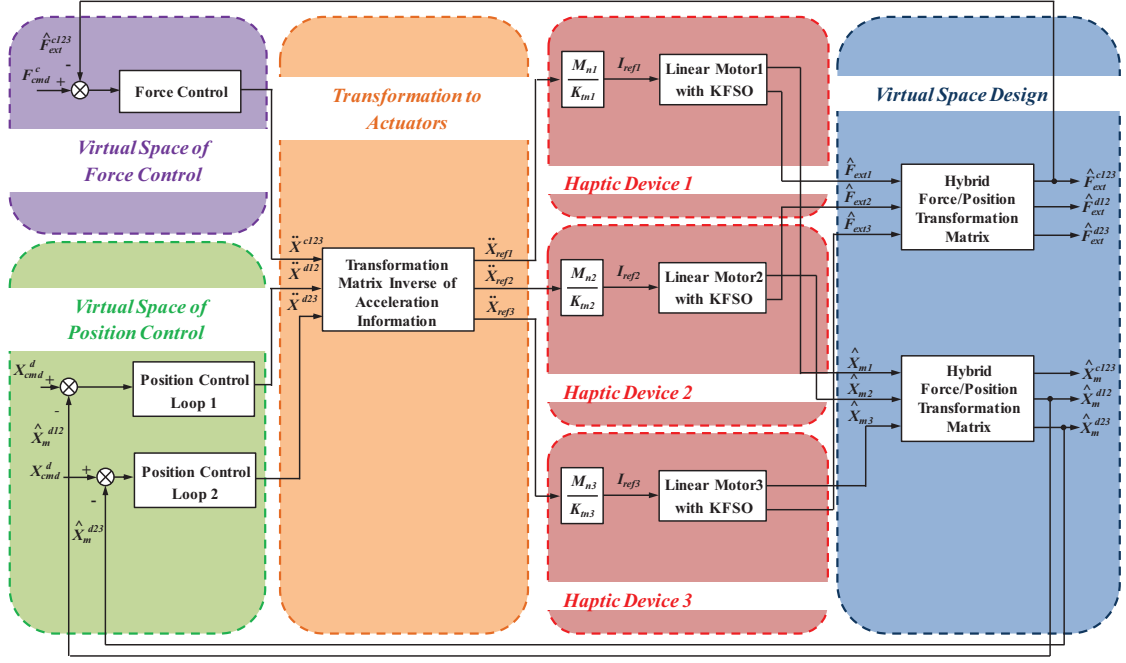


Fig. 4. Block diagram of the proposed multilateral control based on KFSO.

IV. CONTROLLER DESIGN FOR MULTILATERAL CONTROL

The complexities that control of master-slave robots present are synchronization in terms of movements and force. Master and slave robot must be controlled similarly. Thus, the target of the ideal multilateral control is to minimize the difference between the force response in the master side $\hat{F}_{ext1}$ and slave side $\hat{F}_{ext2}, \hat{F}_{ext3}$ as follows,

$$\hat{F}_{ext1} + \hat{F}_{ext2} + \hat{F}_{ext3} = 0 \quad (13)$$

Moreover, the position tracking of the master robot $\hat{X}_{m1}$ and slave robot $\hat{X}_{m2}, \hat{X}_{m3}$ should be similar, as follows,

$$\hat{X}_{m1} = \hat{X}_{m2} = \hat{X}_{m3} \quad (14)$$

Two control modes, namely the common mode and differential mode, are implemented and applied to control both the position and force as shown in Fig. 4. In order to obtain information for the modal space design, the force estimation from the KFSO at the master side, $\hat{F}_{ext1}$, and the KFSO at the slave side, $\hat{F}_{ext2}, \hat{F}_{ext3}$, are transformed into the virtual force in the common mode, $\hat{F}_{ext}^{c123}$, and the differential mode, $\hat{F}_{ext}^{d12}, \hat{F}_{ext}^{d23}$, by using the Hybrid force/position transformation matrix based on the third order of Hadamard matrix, $\mathbf{H}_3$. On the other hand, the position signals from the KFSO at the master side, $\hat{X}_{m1}$, and the slave side, $\hat{X}_{m2}, \hat{X}_{m3}$ are also transformed into the virtual position in the common mode, $\hat{X}_m^{c123}$, and the differential mode, $\hat{X}_m^{d12}, \hat{X}_m^{d23}$, by using the $\mathbf{H}_3$. The virtual position of each mode is represented as follows:

$$\begin{bmatrix} \hat{F}_{ext}^{c123} \\ \hat{F}_{ext}^{d12} \\ \hat{F}_{ext}^{d23} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} \hat{F}_{ext1} \\ \hat{F}_{ext2} \\ \hat{F}_{ext3} \end{bmatrix} \quad (15)$$

$$\begin{bmatrix} \hat{X}_m^{c123} \\ \hat{X}_m^{d12} \\ \hat{X}_m^{d23} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} \hat{X}_{m1} \\ \hat{X}_{m2} \\ \hat{X}_{m3} \end{bmatrix} \quad (16)$$

The force control in the common mode can be separately analyzed as the proportional controller as shown in the following equation,

$$\ddot{X}^{c123} = (F_{cmd}^c - \hat{F}_{ext}^{c123})K_f \quad (17)$$

where F_{cmd}^c is the force command and K_f is the proportional gain of force control. On the other hand, the position control in the differential mode can be analyzed as the proportional-derivative (PD) controller. The modal space designed of each mode is controlled in the acceleration dimension as follows,

$$\ddot{X}^{d12} = (X_{cmd}^d - \hat{X}_m^{d12})(K_{p12} + sK_{d12}) \quad (18)$$

$$\ddot{X}^{d23} = (X_{cmd}^d - \hat{X}_m^{d23})(K_{p23} + sK_{d23}) \quad (19)$$

where X_{cmd}^d is the position command. According to the targets of the bilateral control, both force and position command were set as zero. K_{p12}, K_{p23} and K_{d12}, K_{d23} are the proportional gain and the derivative gain of position control, respectively.

In order to transform into the master robot and slave robot, the transformation matrix inverse matrix $\mathbf{H}_3^{-1}$ is applied. The transformation of acceleration control signals from modal

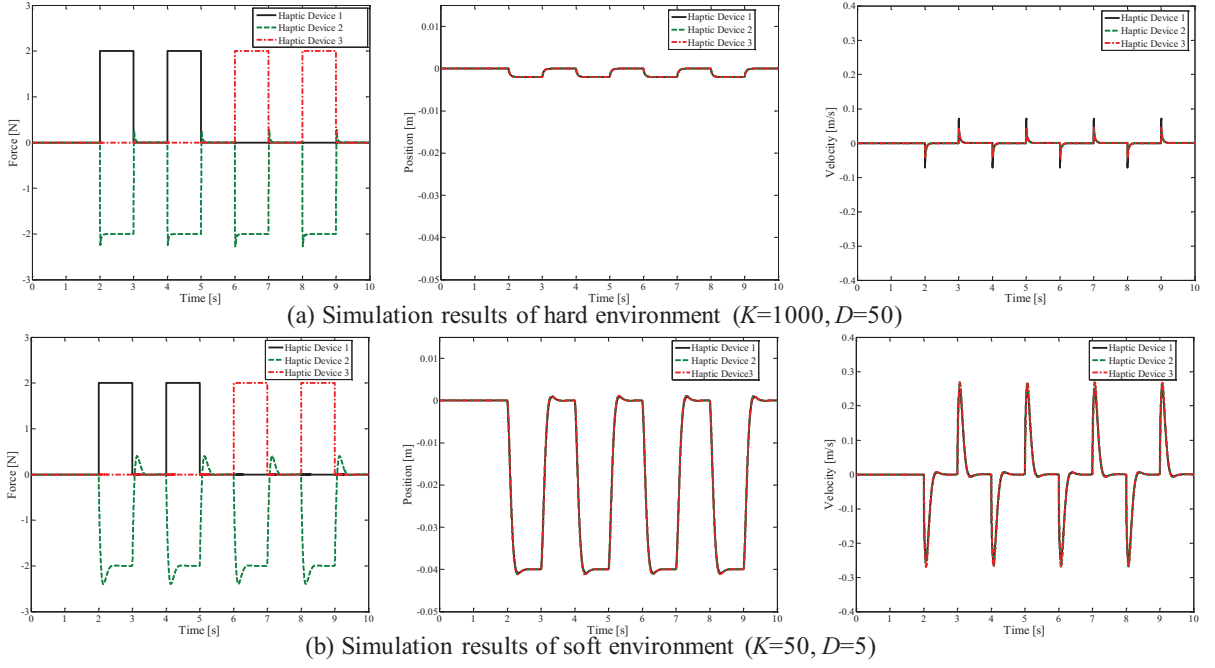


Fig. 5. Simulation results

space design to the real space in the master robot $\ddot{X}_{ref1}$ and slave robot $\ddot{X}_{ref2}$, $\ddot{X}_{ref3}$ are calculated as follows,

$$\begin{bmatrix} \ddot{X}_{ref1} \\ \ddot{X}_{ref2} \\ \ddot{X}_{ref3} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 2 & 1 \\ 1 & -1 & 1 \\ 1 & -1 & -2 \end{bmatrix} \begin{bmatrix} \ddot{X}^{c123} \\ \ddot{X}^{d12} \\ \ddot{X}^{d23} \end{bmatrix} \quad (20)$$

where $\ddot{X}^{c123}$ is the acceleration control signal in the common mode. In the differential mode, $\ddot{X}^{d12}$ is the acceleration control signal between the first and the second haptic devices and $\ddot{X}^{d23}$ is the acceleration control signal between the second and the third haptic device.

V. SIMULATION RESULTS

The simulation was performed to evaluate the performance of the proposed approach with the input pulse function. A teacher operates haptic device 1 at 2.0 s, a student operates haptic device 3 directly at 6.0 s and the haptic device 2 (Slave robot) is contacted to an unknown environment twice times by the end-effectors of the robot. Fig. 5(a) shows the simulation result of hard environment. On the other hand, Fig. 5(b) shows the simulation result of soft environment, respectively.

By using the proposed method, the position response of master side can be tracked almost identically over the position response of slave sides. After the slave robot is moved to contact the soft and hard environment, the force feedback is transmitted to the master robot with very fast response and high bandwidth sensation. It is not necessary to modify parameter gains according to the stiffness of environment. The system is high robustness against the parameter variations, disturbance effects, and unknown environments.

VI. CONCLUSION

In this research, Kalman-filter techniques were employed to estimate action/reaction force of haptic devices. An advantage of Kalman filter is the ability to estimate state variable with noise compensation. Thus, these design techniques overcame limitation in the design of disturbance observer. Moreover, feedback of disturbance compensation loop can also be used to improve the robustness of the multilateral control system.

The modal space design techniques is based upon realizing the Newton's law of action and reaction in order to achieve high transparency of multilateral control. We found that the force and position response of the master robot are almost equal to the slave robot. It is clear that high transparency and good perception of the environmental stiffness with multi-robot system can be achieved successfully. This controller may thus be useful in many application areas, for example, to support a doctor for the surgical operation, and to teach a student in the haptic training system.

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Vibration Suppression of Flexible Three-Mass System Using PID Controller Based on Resonance Ratio Control

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Abstract—Generally, the industrial machine and robot manipulator with the flexible tool can be modeled as the three-mass system. By using the conventional PID controller, this method cannot perform well due to the resonance in the system. Thus, it is necessary to design the controller that guarantees the robustness and suppress vibration. In this paper, a new method is proposed and applied to control the flexible robot by using PID controller based on resonance ratio control. The effectiveness of the proposed method is verified by numerical simulation results. By using the proposed method, the vibration effect can be rejected very successfully in the flexible three-mass system.

Keywords—Three-mass System; Resonance ratio control; Multi-Encoder Disturbance Observer

I. INTRODUCTION

Recently, the automatic machine and robot are very important on an industry. Robots are used in many applications for support human such as medical tools that require accurate force and position control. Generally, force control uses force sensors to measure external force and feedback to the system. However, the force sensor has limitations such as it has low bandwidth and too much noise. The cost of force sensor depends on the size of bandwidth. Most of the force sensors have structural vibration due to the soft structure of the strain gauge. In order to solve this problem, resonance ratio control based on disturbance observer is proposed by Yuki [1]. In addition, the sensorless force servoing system based on resonance ratio control was proposed by Katsura [2]. Then Mitsantisuk proposed multi-encoder based disturbance observer (MEDOB) to estimate the force response from two-mass system [3-5]. This research proposes a novel technique to compensate the vibration effect of flexible three-mass system by using PID controller based on resonance ratio control with MEDOB.

This paper is composed of four parts. In part II, a basic structure of a three-mass system is shown. Next, the disturbance observer is used to guarantee the robust force control. Then the reaction torque estimation method based on MEDOB is also explained. The collaborative PID controller with the resonance ratio control is shown in part III. Part IV

shows the simulation results and the conclusions of the proposed approach.

II. THREE MASS SYSTEM

A. The model of three-mass system

The model of three-mass system has the same structure as two-mass system, but three-mass system has two loads. Three-mass system consists of a motor M , two loads L_1 and L_2 connected by a flexible structure to transmit the actuator torque to a distant joint as shown in Fig. 1. Therefore, the elasticity of flexible robot is realized under assumptions that it can be modeled by constant spring coefficient K_s and mass system [6].

A block diagram of the linear motor with three-mass system that controls under the ideal current source is shown in Fig. 2. The dynamic equation of the linear motor is described by:

$$\ddot{X}_m = -\frac{K_{s_1}}{M} X_{s_1} + \frac{K_t}{M} I_m, \quad (1)$$

$$\ddot{X}_{l_1} = \frac{K_{s_1}}{L_1} X_{s_1} - \frac{K_{s_2}}{L_1} X_{s_2}, \quad (2)$$

$$\ddot{X}_{l_2} = \frac{K_{s_2}}{L_2} X_{s_2} - \frac{1}{L_2} F_{dl_2}, \quad (3)$$

$$\dot{X}_{s_1} = \dot{X}_m - \dot{X}_{l_1}, \quad (4)$$

$$\dot{X}_{s_2} = \dot{X}_{l_1} - \dot{X}_{l_2}, \quad (5)$$

where subscripts m and l denote the motor side and load side, respectively. X_s is the torsional position from the position of the motor X_m and the position of the load X_l , M and L denote the equivalent mass of the motor and load mass, respectively. F_{dl} is the external force on the load side. $\ddot{X}$ and $\dot{X}$ denote the acceleration and velocity, respectively.

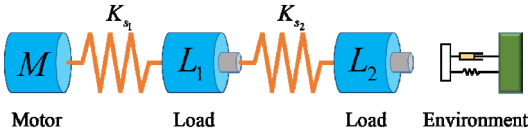


Fig. 1. The model of three-mass system.

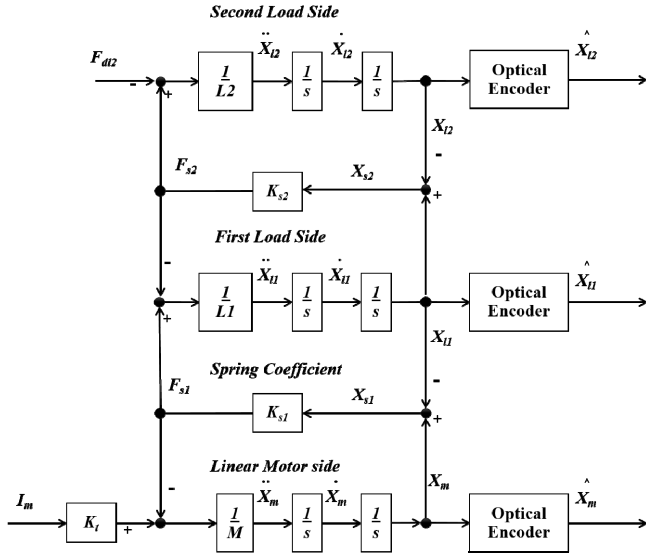


Fig. 2. The block diagram of three-mass system.

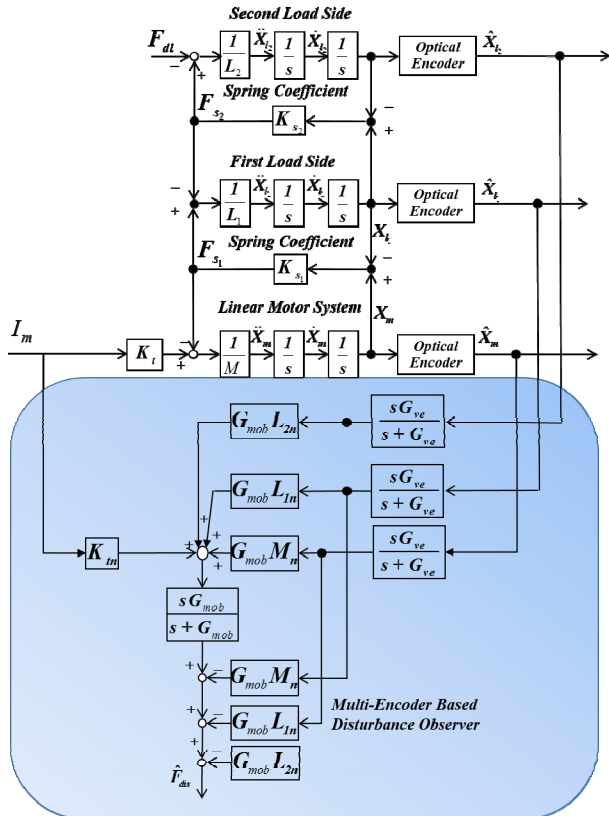


Fig. 3. Multi-encoder based on disturbance observer.

B. Disturbance Observer

Disturbance observer is an external disturbance estimation algorithm that is based upon motor current and velocity information[1]. The disturbance observer has been used for improving the robustness and bandwidth of the control system. It has been guarantee a robust force control, when the disturbance observer is implemented as the feed forward control for a disturbance force compensation loop as shown in the next section.

C. Multi-Encoder based on disturbance observer

Generally, a force sensor has been widely applied to measure the external force information [7-9]. However, the bandwidth of the force sensor is not very high since the strain gauge with soft structure is used. Moreover, the information of the force sensor has much noise. Thus, the deterioration to use of force sensor is the presence of significant oscillation in the system. Based on the sensorless force control technology, a disturbance observer can be used instead of the real force sensor. But, instability and vibration of system can occur when using disturbance observer for the flexible robot system because of the presence of spring that degrade the overall performance. To solve this problem, a load disturbance observer (LDOB) is proposed to estimate the external force at the load side. However, the exact parameters of the spring coefficient are difficult to obtain. Moreover, it can be assumed by a non-linear relationship.

A multi encoder based disturbance observer (MEDOB) is used to estimation the external force at the load side of flexible three-mass system as shown in Fig. 3. It is not necessary to estimate the nominal spring coefficient parameters. The method to estimate the external force at the load side is obtained from the equation and a simple first-order low-pass filter as follows,

$$F_{dl} = K_t I_m - L_1 \ddot{X}_{l1} - L_2 \ddot{X}_{l2} - M \ddot{X}_m \quad (6)$$

$$\hat{F}_{dl} = \frac{G_{mob}}{s + G_{mob}} (K_{tm} I_m + G_{mob} M_n \hat{\dot{X}}_m + G_{mob} L_{1n} \hat{\dot{X}}_{l1} + G_{mob} L_{2n} \hat{\dot{X}}_{l2}) - G_{mob} M_n \hat{\dot{X}}_m - G_{mob} L_{1n} \hat{\dot{X}}_{l1} - G_{dis} L_{2n} \hat{\dot{X}}_{l2} \quad (7)$$

Compared to the other conventional ways such as state observer and LDOB, MEDOB offers the advantages of faster response, and high accuracy.

III. CONTROL SYSTEM

A. Resonance ratio control

The simplified block diagram of this reaction force feedback is shown in Fig. 4. The controllers of robot system consist of a force gain K_p , a velocity gain K_{v1} , K_{v2} , a reaction force gain K_{r1} , K_{r2} . The feedback force will depend on the force contacted on the robot by a known environment stiffness K_e . The transfer function from the force command F_{cmd} to the force response F_{res} can be calculated as follows,

$$\frac{F_{res}}{F_{cmd}} = \frac{K_e K_p K_{s1} K_{s2}}{a_6 s^6 + a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0} \quad (8)$$

$$a_0 = K_e K_p K_{s1} K_{s2}, \quad (9)$$

$$a_1 = K_{s1} K_{s2} K_{v1} + K_{s1} K_{s2} K_{v2}, \quad (10)$$

$$a_2 = K_{s1} K_{s2} + K_{s1} K_{s2} L_1 + K_{s1} K_{s2} L_2 + K_{r1} K_{s1} K_{s2} L_1 + K_{r2} K_{s1} K_{s2} L_2, \quad (11)$$

$$a_3 = K_{s1} K_{v1} L_2 + K_{s2} K_{v1} L_1 + K_{s2} K_{v1} L_2, \quad (12)$$

$$a_4 = K_{s1} L_2 + K_{s2} L_1 + K_{s2} L_2 + K_{s1} L_1 L_2 + K_{r1} K_{s1} L_1 L_2, \quad (13)$$

$$a_5 = K_{v1} L_1 L_2, \quad (14)$$

$$a_6 = L_1 L_2, \quad (15)$$

K_{r1} , K_{r2} , K_{v1} , and K_{v2} have affected in characteristic equation of the transfer function. This means that the resonance frequency of the system can be changed to an arbitrarily value which it extends bandwidth for better control of higher frequency input as shown in the results.

B. PID Controller

PID controller is used to adjust the transient and error of the system. The output $U(t)$ of the PID controller is

$$U(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d e(t) \quad (16)$$

Where, K_p , K_i and K_d are the proportional, integral and derivative gains, respectively. $e(t)$ is the error between the reference input $r(t)$ and the output $y(t)$ at time t .

In three-mass system, it has vibration effect. Therefore, only PID controller cannot be used to control the three-mass system. In this paper, the PID controller based on resonance ratio control has been used for improving the force response and bandwidth of the system. The PID controller based on resonance ratio control has two feedback reaction forces F_{s1} , F_{s2} and feedback velocity of motor $\dot{x}_m$ and feedback velocity at load side $\dot{x}_{l2}$. The block diagram is shown in Fig. 5.

IV. RESULTS AND CONCLUSIONS

A. Results

In the simulation results, the force command input is applied by a step function with the magnitude of 1.0 N as shown in Fig. 6. The PID controller gives a poor response with overshoot and vibration. For using PID controller based on resonance ratio control, the force response has shorter setting time and smaller error than PID controller without resonance ratio control. In the simulation of soft environment, it has a little vibration as shown in Fig. 6 (a). On the other hand, the oscillation effect is occurred in the force response of the simulation result of the hard environment as shown in Fig. 6. (b). The position response of each type of environment is shown in Fig.7. It has the same effect as shown in the force response. The specifications of the linear motor and the parameters used in the simulations are shown in Table 1.

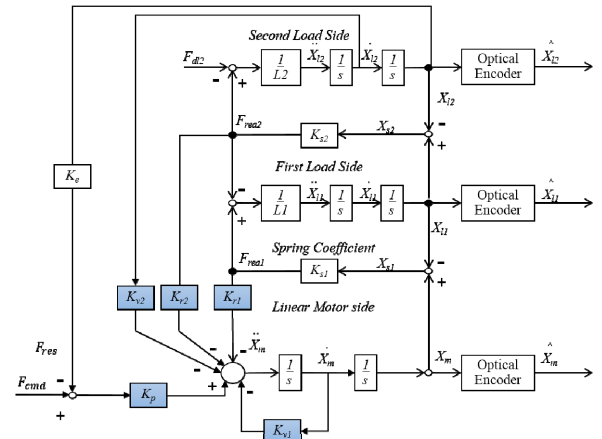


Fig. 4. The simplified block diagram of the resonance ratio control.

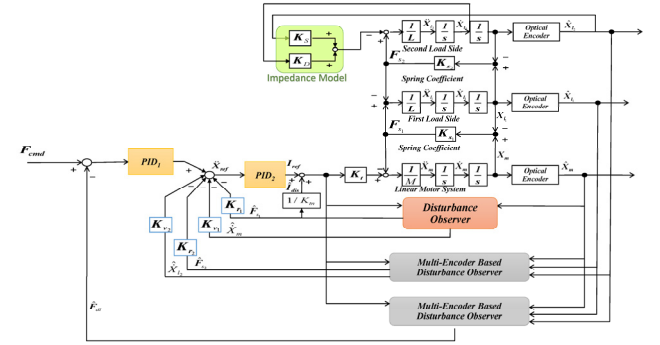
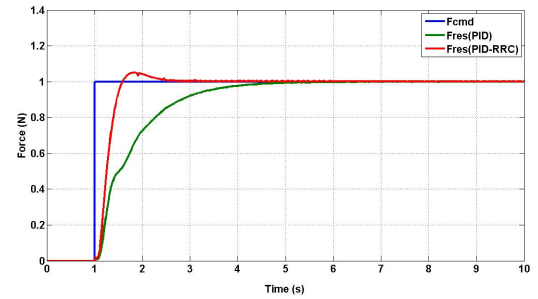
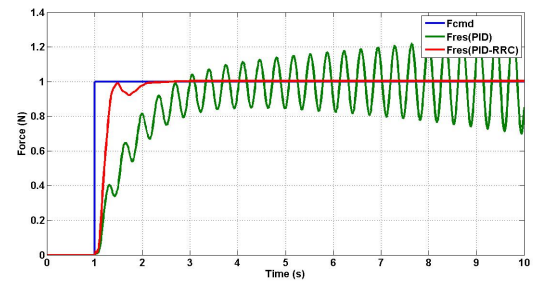


Fig. 5. PID controller based on resonance ratio control.



(a) Soft environment.



(b) Hard environment.

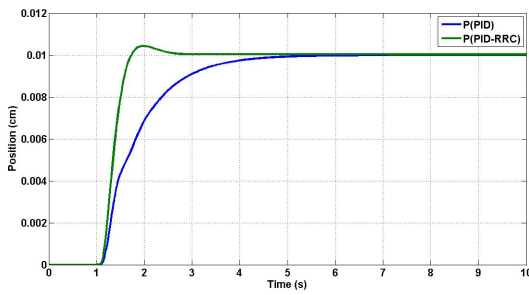
Fig. 6. The force response of three-mass system.

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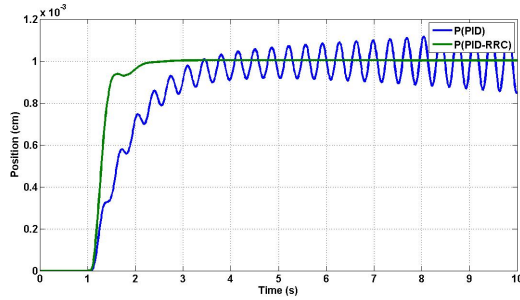
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(a) Soft environment.



(b) Hard environment.

Fig. 7. The position response of three-mass system.

TABLE I. PARAMETERS USED IN SIMULATIONS

Details	Parameters	Values
Mass of Motor	M	0.245 kg
Load	L_1, L_2	0.245 kg
Force Constant	K_t	3.333
Environment stiffness	K_e	110
Spring coefficient	K_{s1}, K_{s2}	200, 220 N/m
Cut-off freq. of velocity.	G_{ve}	250 rad/s
Cut-off freq. of DOB.	G_{dis}	250 rad/s
Cut-off freq. of MEDOB.	G_{mob}	250 rad/s
Proportional gain	K_{p1}, K_{p2}	2.2973, 7.0498e-05
Integral gain	K_{i1}, K_{i2}	13.0104, 0
Derivative gain	K_{d1}, K_{d2}	-0.0739, 0.0015

B. Conclusions

In this paper, the PID controller based on resonance ratio control and MEDOB is proposed. It can be found in the results that the proposed method can reduce vibration and error of the system even if the environment is changed. This method can be applied in many applications which system has more than two or three masses such as surgery, high resolution milling. Moreover, the proposed method can be used to improve the better performance for the future robot applications.

A Spectrogram Analysis of Impact Force Response in a Tele-operated Robot System

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Abstract—Recently, robots have been used in many applications. A necessary ability is discrimination of the objects. The hardness of each object is analyzed for design the controller of the robot system. This paper proposes a methodology to discriminate objects by mean of spectrogram analysis. The force signals are obtained by knocking of master-slave robot and then improved by Disturbance Observer (DOB). Finally, the spectrogram of force signal is analyzed to discriminate the objects. The simulation results demonstrate the effectiveness of the proposed method.

Keywords—Disturbance Observer, Bilateral Control System, Master-Slave Robot, Short-Time Fourier Transform, Spectrogram

I. INTRODUCTION

Many researches used the knocking sound signal or signal compression to classify the kinds of objects. However, the sound signal always come with high noise and consequently while the signal compression gives the lower noise. However it partly damage the data and the distortion could be occurred. For these reasons, the analysis force response has become more interesting method.

Bilateral control robots which consist of master and slave robot is used in many haptic communication system [1]-[2]. Due to higher noise level and low bandwidth of force sensor the Disturbance Observer (DOB) was used To estimate disturbance force instead [3]

This paper proposes the effective method by analysis the force response through the spectrogram. The master-slave robot is used to knock the objects which have different hardness. The force response are analysis by mean of spectrogram to classify the objects [4]. This paper consists of 5 sections. The section 2 shows the DOB and bilateral control system of master-slave robot. In section 3, spectrogram analysis is described The simulation results and discussions are demonstrated in section 4. Finally, the last section summarized the paper.

II. BILATERAL CONTROL SYSTEM BASED ON DISTURBANCE OBSERVER

This section describes the bilateral control system and DOB for controlling master-slave robot

A. Disturbance Observer

The purpose of Disturbance observer (DOB) is to estimate disturbance force at motor and feed back for compensation and improvement the robustness and bandwidth of the system. The structure of DOB is shown in Fig. 1.

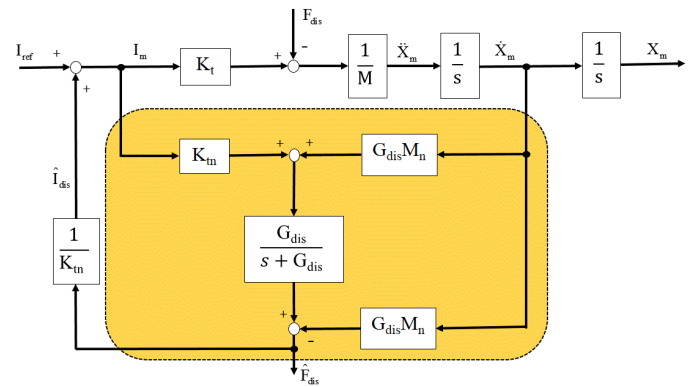


Fig 1. Disturbance Observer (DOB)

Where M denotes the mass of the motor, K_t denotes the force coefficient. I_m is the current of motor, F_{dis} is disturbance force and G_{dis} is the cut-off frequency of the low-pass filter for design the bandwidth of observer respectively. Using a low bandwidth, it can reduce a high-frequency noise. $\ddot{X}_m$, $\dot{X}_m$ and X_m represent acceleration, velocity and position of the motor respectively. The disturbance force F_{dis} estimated by DOB is fed back to the system for robust control.

B. Bilateral Control System

The bilateral control system is consists of master and slave robot which control similarly. And its control goals are represented as follows,

$$F_m + F_s = 0 \quad (1)$$

$$X_m - X_s = 0 \quad (2)$$

where F_m and F_s are the force at master robot side and slave robot side. X_m and X_s are the position of master and slave robot respectively.

Eq. (1) represents the law of action and reaction. Force at master robot side is equal the force at slave robot side but opposite in direction. Eq. (2) represents position tracking of master and slave robot. Master robot position is equal to slave robot position.

The virtual spaces of force and position at master and slave side using Hadamard matrix are as follow:

$$\begin{bmatrix} \hat{F}_{ext}^c \\ \hat{F}_{ext}^d \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \hat{F}_{dis}^m \\ \hat{F}_{dis}^s \end{bmatrix} = H_2 \begin{bmatrix} \hat{F}_{dis}^m \\ \hat{F}_{dis}^s \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} \hat{X}_{ext}^c \\ \hat{X}_{ext}^d \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} X_{dis}^m \\ X_{dis}^s \end{bmatrix} = H_2 \begin{bmatrix} X_{dis}^m \\ X_{dis}^s \end{bmatrix} \quad (4)$$

Eq. (3) – (4) comprise common and differential mode of force and position. The subscript c is a common mode and subscript d is a differential mode. The structure of bilateral control system based on DOB system is shown in Fig. 2.

III. ANALYSIS FORCE RESPONSE BY USING SPECTROGRAM

A. Spectrogram

The Fourier Transform is a basic theory to extract the frequency component of stationary signal. But in real word, the signals are non-stationary i.e. vary with time. To deal with

the non-stationary signal, the spectrogram analysis together with Fourier Transform are applied in this paper.

Spectrogram is a graph with three geometric dimensions. X axis represents time and Y axis represents frequency and Z axis represents amplitude of the signal respectively.

Considering X-Y plane, warm colors represent a high amplitude of force response. While the cool colors represent a low amplitude of force response. The spectrogram could be calculated from Short-Time Fourier Transform (STFT) as shown in Fig. 3. Eq. (5) shows STFT equation. $X(n)$ is separated into short parts by sliding window function $w(n)$.

$$X_{STFT}(e^{j\omega}, n) = \sum_{m=-\infty}^{\infty} X(n-m)w(m)e^{-j\omega m} \quad (5)$$

Window function must be overlap between other windows. It can be described on two spectrogram depend on window length, wideband spectrogram and narrowband spectrogram. The narrow window gives wideband spectrogram compared with that from the wider window. The spectrum magnitude of each window is calculated by Fast-Fourier Transform (FFT) and then the window function is shifted in time domain. Finally, the results are displayed in the spectrogram.

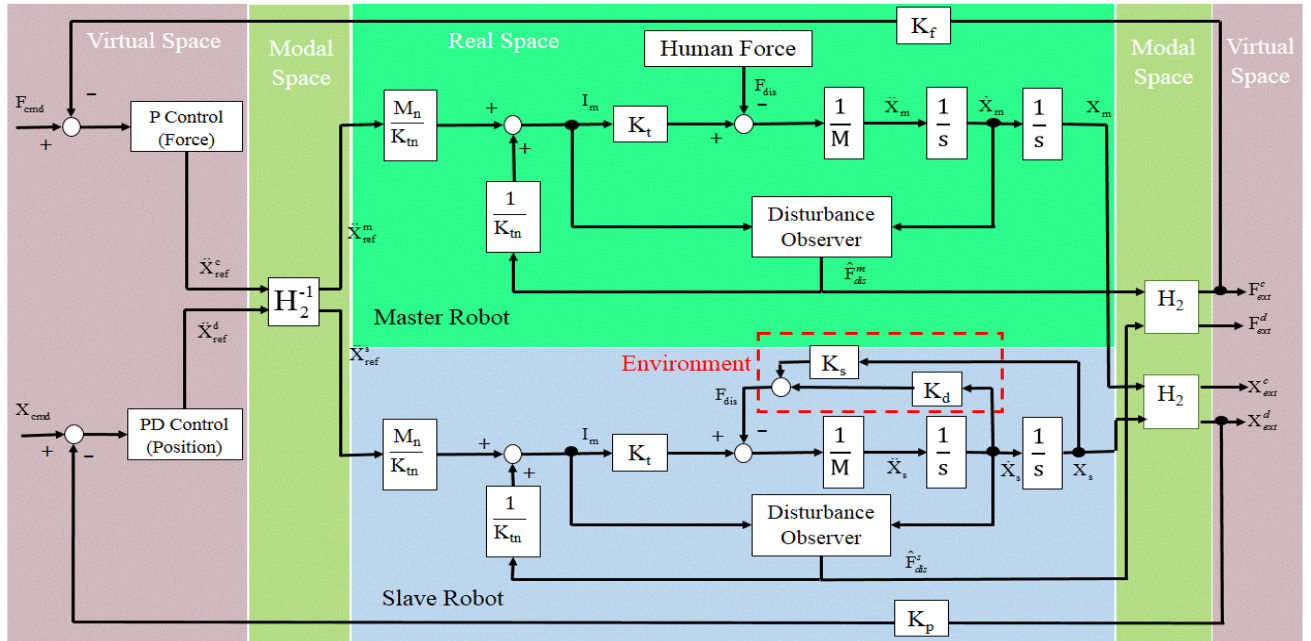


Fig 2. The block diagram of bilateral control system based on disturbance observer

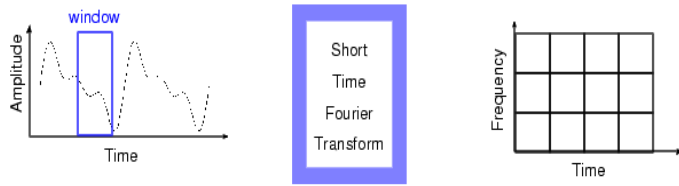


Fig 3. Short-Time Fourier Transform (STFT)

IV. EXPERIMENT AND RESULT

A. Experimental Setup

The master-slave robot is used for knocking the objects and collect force data through DOB. The master robot is received the unit step input of human force with initial time at 5 second as shown in Fig. 4. The slave robot move to contact the object with the same unit step input force of master robot. DOB estimates interaction force when the slave robot contact the object. The spectrogram of force is then analyzed the hardness of the object and the discrimination results are presented. The experiments perform on the 3 different hardness objects. The hardness is controlled by adjusting stiffness K_s and damping K_d gain of the impedance control.

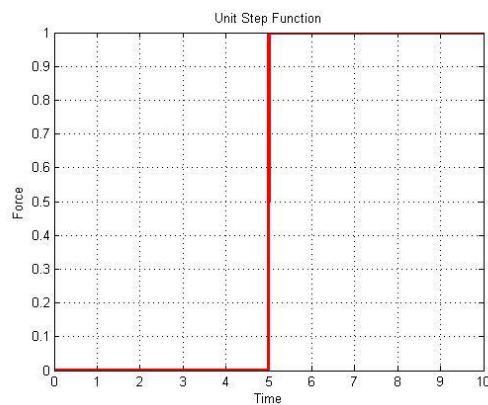


Fig 4. Unit step input at initial time 5 s

B. Experimental Result I

Fig. 5-7 show the force response in the case of stiffness gain 1, 10 and 100 respectively. In Fig. 5 force response is less than one of Fig. 6 and 7 which has a higher gain. The higher hardness the objects have, the higher the force response they produce. This because the hard object produce more vibration than that of soft object. Hard object has a force response more than soft object. Therefore, hard object has more vibrating than soft object.

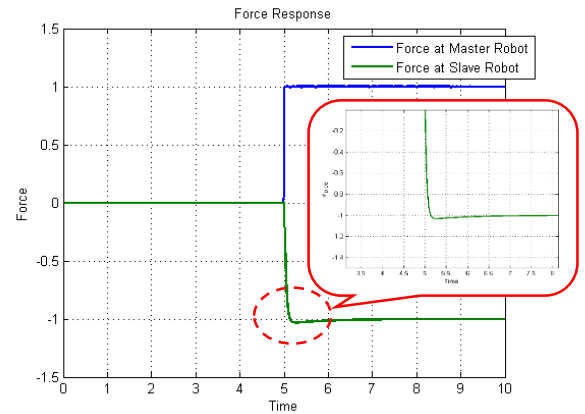


Fig 5. Force response of the object (gain 1)

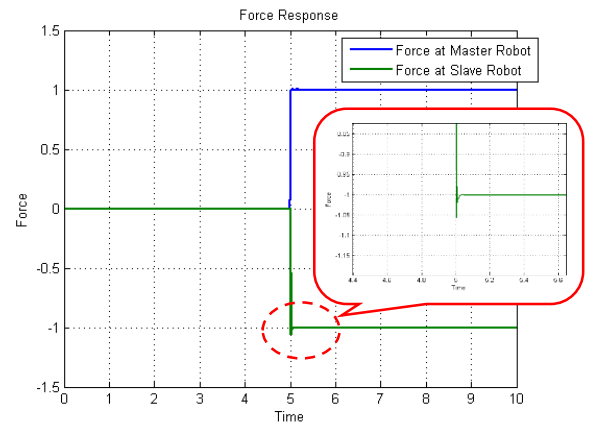


Fig 6. Force response of the object (gain 10)

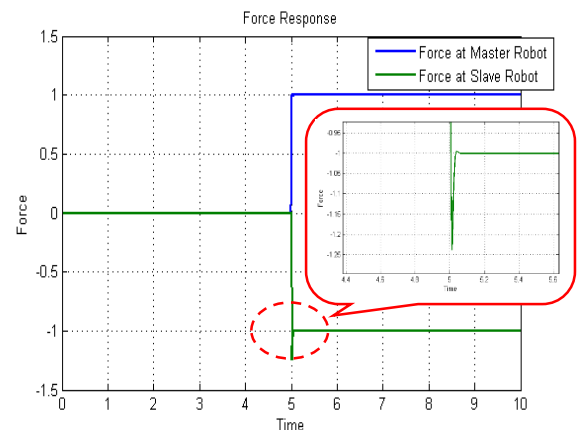


Fig 7. Force response of the object (gain 100)

C. Experimental Result II

Fig. 8 shows the spectrogram of force response with gain 1. According to the results, the red square box shows the vibration of force response at the low frequency.

Fig. 9 shows spectrogram of force response with gain 10. The vibration in this case occurs at higher frequency compared with the former case.

Fig. 10 represents spectrogram of force response with gain 100 which is the highest hardness in the experiments. Obviously, the result shows the vibration at the highest frequency compared with the two previous cases.

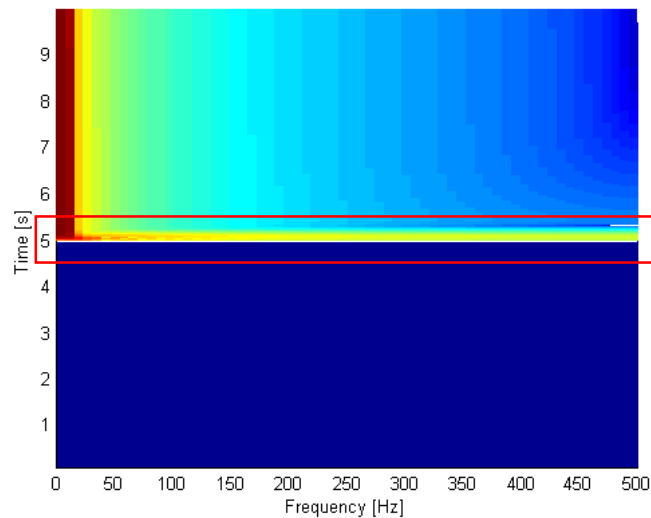


Fig 8. Spectrogram of force response (gain 1)

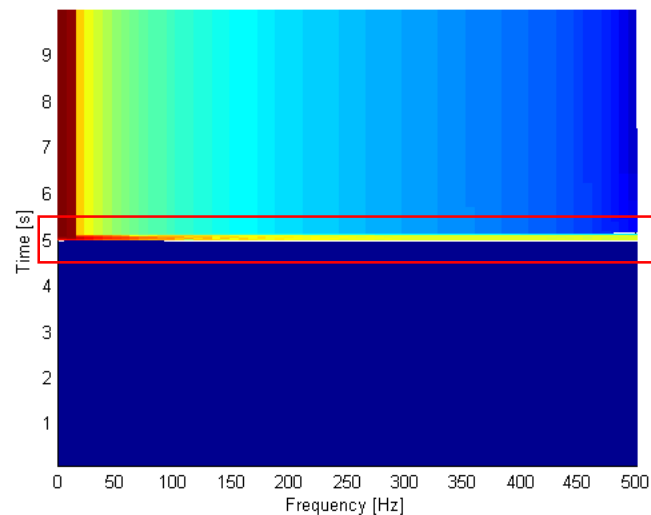


Fig 9. Spectrogram of force response (gain 10)

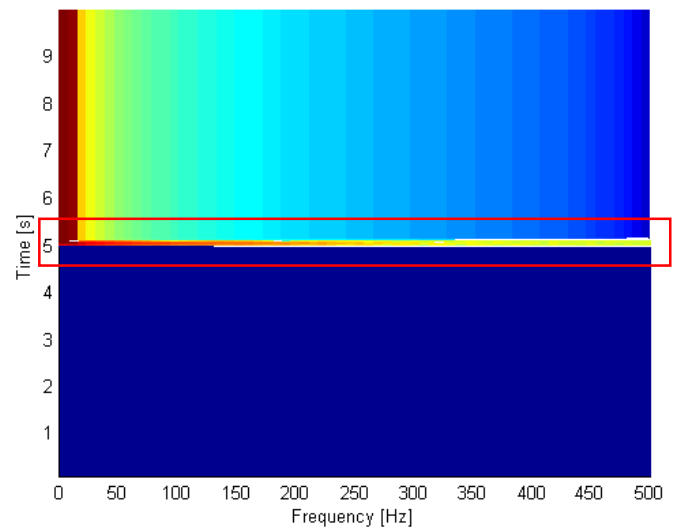


Fig 10. Spectrogram of force response (gain 100)

V. CONCLUSION

This paper presents the application of the spectrogram to discriminate objects. Bilateral control system based on DOB is implemented on master-slave. The objects can be discriminated by the spectrogram analysis of force response. From the experimental results, the spectrogram analysis show the vibrations of force response at the different frequency. To the proposed method is simply to classify the objects. For the future work, the method will be applied to the sound and compression signal.

ACKNOWLEDGEMENT

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Transparency Improvement in A Bilateral Motion-Scaling Control Using Kalman-Filter-Based Disturbance Observer

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Abstract—This paper proposes a new wideband bilateral motion-scaling control to apply in the small size robot system. The scaling Hadamard matrix is applied to reduce or magnify the force and position response of bilateral motion-scaling control. The technique to estimate the action/reaction forces of master-slave robot is designed using Kalman-filter based disturbance observer (KFDOB). Optical encoder and acceleration signals were fused to estimate contact forces occurring during an experiment. With the bilateral motion-scaling control and KFDOB, we can control the small scale master-slave robot with high precision. Comparative experiments show the KFDOB and its multi-sensor fusion to provide performance superior to that of previously disturbance observer. As seen in the experimental results, it is clear that high transparency and good perception of the environmental stiffness with the response of the master-slave robot can be achieved successfully. An additional result of FFT analysis which guarantees noise compensation is also presented.

I. INTRODUCTION

Recently, robot systems are increasingly applied in many applications to support human operators. The development of a robot collaborating with human operators provides an effective applicability in which the intelligence and experience of human operators are combined with the accuracy and repeatability of the robot system. Human support robot is a widely discussed field. For example, the da Vinci surgical system [1] and ZEUS surgical system have been introduced to perform the surgery effectively. Search and rescue robot [2] provides an ability to detect and identify victims by using various sensors on multiple robots and enables the operator to control the robot as desired.

For a more flexible usage of robot systems, The ability to feedback force sensation is another important performance specification in order to increase safety. Several researchers have applied the bilateral control in order to feedback force sensation to human operator. The bilateral control system consists of master and slave robots assembled for the purpose of obtaining a same action of force and motion movements with desired performance. One of the drawbacks of bilateral control, using force sensor [3], is that undesirable oscillations is occurred due to the sensor noise.

Generally, a task operation in the robot system may involve more than one dimensional scale at the same time.

For example, the slave robot can be used to operate task in dangerous locations or in a small space by controlling the master robot. To develop the applications for specific task, several researchers have designed the method to make the system function in different scaled environment as shown in Fig. 1. Previous work on this problem has been motivated by using a disturbance observer [4], [5]. Nevertheless, the problem of sensor noise with a small sensory device, such as undesirable oscillations and instability, does not only degrade the performance at the slave side but also at the whole system. By using the low bandwidth of the observer, the smoothing sets of force data without noise are obtained. However, both the stability and response of the force control system are deteriorated. Therefore, the sensor noise represents a major performance impairment that must be compensated.

To provide correct feedback of action/reaction force with low noise, Kalman-filter-based disturbance observer is proposed. Moreover, the scaling Hadamard matrix is also applied to reduce or magnify the force and position response of bilateral control. As the proposed algorithm transforms and controls an acceleration information according to Newton's law of action and reaction, this feature may make it very useful to apply in the bilateral motion-scaling control with high transparency of force sensation.

The rest of paper is organized as follows: In section 2, the modeling of master-slave robot is described. In section 3, we review one previously reported disturbance observer and present a Kalman-filter based disturbance observer. In section 4, the structure of the bilateral motion-scaling control based on the scale ratio of Hadamard matrix is explained. In section 5, we present comparative experimental results of position and force responses which corroborate the theory and compare the performance of the proposed method with the conventional method. It is clear that high transparency and good perception of the environmental stiffness with the response of the small scales of master-slave robot can be achieved successfully. An additional result of FFT analysis which guarantees noise compensation is also presented. Section 6 concludes and summarizes the results.

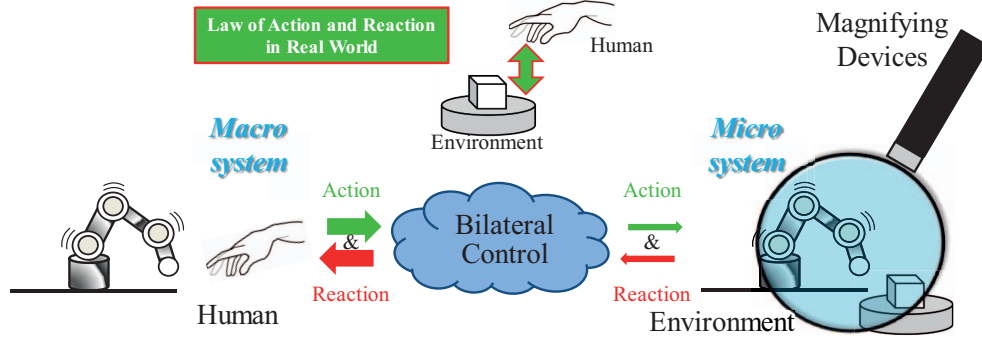


Fig. 1. Overview of the Macro-Micro Bilateral Control.

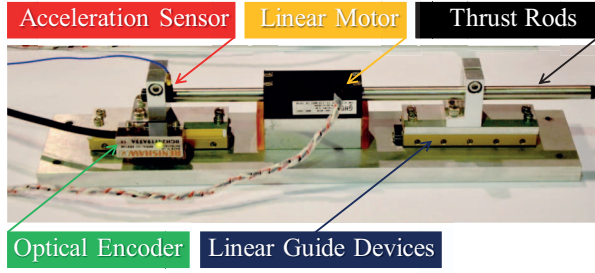


Fig. 2. Linear motor systems with multi-sensor fusion.

II. MODELLING OF THE MASTER-SLAVE ROBOT

The system hardware of haptic device consists of linear motors, linear guide devices, and motion sensors as shown in Fig. 2. The next step is to develop mathematical modelling of the master-slave robot from schematics of physical system. A model of the linear motor regulated under the ideal current source is shown in Fig. 3. From this figure, the dynamic equation of the linear motor based on translational mechanical system is described by

$$M\ddot{X}_m = K_t I_m - (F_f + D\dot{X}_m + F_{ext} + \Delta M\ddot{X}_m + \Delta K_t I_m) \quad (1)$$

$$F_l = F_f + D\dot{X}_m + F_{ext} \quad (2)$$

where, M denotes the motor mass. X_m , $\dot{X}_m$ and $\ddot{X}_m$ denote the motor position, motor velocity and motor acceleration, respectively. K_t is the force coefficient, and I_m is motor current. The load force F_l is the summation of friction force F_f , viscous friction $D\dot{X}_m$ and external force F_{ext} . The equation of the load force is considered as (2). $\Delta M\ddot{X}_m$ is the variation torque due to changed mass, $\Delta K_t I_m$ is the force ripple due to space harmonics. The disturbance force on the motor side F_{dis} is defined as,

$$F_{dis} = F_f + D\dot{X}_m + F_{ext} + \Delta M\ddot{X}_m + \Delta K_t I_m \quad (3)$$

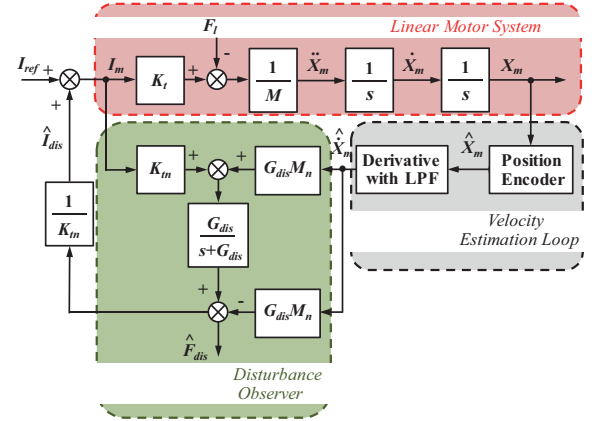


Fig. 3. Modeling of Linear Motor System with DOB.

III. MOTION SENSOR-BASED EXTERNAL FORCE ESTIMATION

A. Disturbance Observer (DOB)

The structure of disturbance observer [4], [5] is shown in Fig. 3. The method to estimate the velocity is obtained from a derivative with simple first-order of low-pass filter as follows,

$$\hat{F}_{dis} = \frac{G_{dis}}{S + G_{dis}} (K_{tn} I_m + G_{dis} M_n \hat{X}_m) - G_{dis} M_n \hat{X}_m \quad (4)$$

$$\hat{X}_m = \frac{SG_{ve}}{S + G_{ve}} \hat{X}_m \quad (5)$$

where G_{dis} is the cut-off frequency of the disturbance observer, G_{ve} is the cut-off frequency of the velocity estimation. K_{tn} and M_n are the nominal force coefficient and nominal mass parameters, respectively. The low-pass filter is used to design bandwidth of force estimation.

A robust motion control of each motor has been achieved by feedback the inner disturbance observer loop. By using the divider's gain $1/K_{tn}$, the disturbance force is transformed to the compensation current $\hat{I}_{dis}$, and it is utilized to cancel out the disturbance on the motor side and the uncertainty of a system due to the parameter variation. Because of the advantages

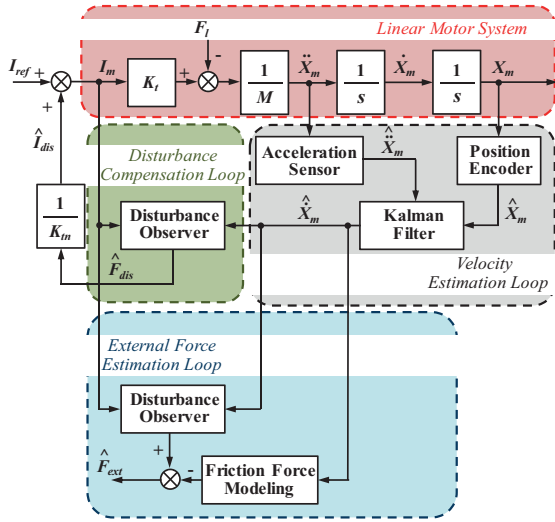


Fig. 4. Modeling of Linear Motor System with KFDOB.

and unique features of disturbance observer, this approach has received much attention in sensorless force control system. However, instability and vibration of system can occur when using disturbance observer for industrial applications because the presence of white Gaussian noise is deteriorated at any range of frequency. Since acceleration sensors is analog output, it have both continuous time noise and quantization noise terms.

B. Kalman-Filter Based Disturbance Observer (KFDOB)

To address these problems, KFDOB, which is composed of disturbance observer [4], [5] and Kalman filter [6], has been proposed. The formulation of the Kalman filter equation is based on state space formulation. A discrete sensor dynamics model can be formulated in the state space form as

$$\mathbf{x}_{(k+1)} = \mathbf{A}_{(k)}\mathbf{x}_{(k)} + \mathbf{B}_{(k)}\mathbf{u}_{(k)} + \mathbf{w}_{(k)} \quad (6)$$

$$\mathbf{z}_{(k)} = \mathbf{C}_{(k)}\mathbf{x}_{(k)} + \mathbf{v}_{(k)} \quad (7)$$

where k represents the sampling instant, $\mathbf{x}_{(k)} \in \mathfrak{R}^n$ is the vector of states, $\mathbf{u}_{(k)} \in \mathfrak{R}^m$ is the vector of input variables, $\mathbf{A}_{(k)} \in \mathfrak{R}^{n \times n}$ and $\mathbf{B}_{(k)} \in \mathfrak{R}^{n \times m}$ are system matrices, $\mathbf{C}_{(k)} \in \mathfrak{R}^{s \times n}$ is the measurement matrix, $\mathbf{z}_{(k)} \in \mathfrak{R}^s$ is the vector of measured variables, $\mathbf{w}_{(k)}$ is the process noise and $\mathbf{v}_{(k)}$ represents the measurement which is corrupted by white Gaussian noise. The system matrices can be formulated into the discrete state matrices as,

$$\mathbf{A} = \begin{bmatrix} 1 & T_k & \frac{T_k^2}{2} \\ 0 & 1 & T_k \\ 0 & 0 & 1 \end{bmatrix}, \mathbf{B} = \begin{bmatrix} 0 \\ \frac{K_{tn}T_k}{M_n} \\ 0 \end{bmatrix}, \quad (8)$$

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where T_k is a sampling time of the controller. It is assumed that the covariance matrix of the process noise $\mathbf{Q}$, the co-

variance matrices of the measurement noise $\mathbf{R}$ and the cross-covariance matrix are as given below:

$$\mathbf{Q} = E\{\mathbf{w}\mathbf{w}^T\} > 0 \quad (9)$$

$$\mathbf{R} = E\{\mathbf{v}\mathbf{v}^T\} \geq 0 \quad (10)$$

$$E\{\mathbf{w}\mathbf{v}^T\} = 0 \quad (11)$$

The matrices $\mathbf{Q}$ and $\mathbf{R}$ are used to tune the accuracy and response of the observer, and these values can be determined by using the simulations for the testing of the measurement sensors. A compromise between the performance of observer and the compensation of acceleration signal noise can be found. The error covariance matrices $\mathbf{P}$ is the variance of the difference between the state and the measurements. The predicted equation which projects the current state estimate ahead in time are given by

$$\mathbf{x}_{(k|k-1)} = \mathbf{A}_{(k-1)}\mathbf{x}_{(k-1|k-1)} + \mathbf{B}_{(k-1)}\mathbf{u}_{(k-1)} \quad (12)$$

$$\mathbf{P}_{(k|k-1)} = \mathbf{A}_{(k-1)}\mathbf{P}_{(k-1|k-1)}\mathbf{A}_{(k-1)}^T + \mathbf{Q}_{(k-1)} \quad (13)$$

The Kalman filter gain matrix $\mathbf{M}$, that is based on the total uncertainty measurement of matrix $\mathbf{S}$ is computed by using the following equation

$$\mathbf{S}_{(k)} = \mathbf{C}_{(k)}\mathbf{P}_{(k|k-1)}\mathbf{C}_{(k)}^T + \mathbf{R}_{(k)} \quad (14)$$

$$\mathbf{M}_{(k)} = \mathbf{P}_{(k|k-1)}\mathbf{C}_{(k)}^T\mathbf{S}_{(k)}^{-1} \quad (15)$$

The estimated state vector and the error matrix are updated by an actual measurement $\mathbf{z}_{(k)}$ of motion sensor at every sampling instant as follows

$$\mathbf{x}_{(k|k)} = \mathbf{x}_{(k|k-1)} + \mathbf{M}_{(k)}(\mathbf{z}_{(k)} - \mathbf{C}_{(k)}\mathbf{x}_{(k|k-1)}) \quad (16)$$

$$\mathbf{P}_{(k|k)} = \mathbf{P}_{(k|k-1)} - \mathbf{M}_{(k)}\mathbf{S}_{(k)}\mathbf{M}_{(k)}^T \quad (17)$$

IV. CONTROLLER DESIGN FOR BILATERAL MOTION-SCALING CONTROL

The complexities that control of master-slave robots present are synchronization in terms of movements and force. Master and slave robot must be controlled similarly. Thus, the target of the ideal bilateral control is to minimize the difference between the force response in the master side $\hat{F}_{ext1}$ and slave side $\hat{F}_{ext2}$. We now write the equation of motion using Newton's law to sum to zero all of the forces as follows,

$$\hat{F}_{ext1} + \hat{F}_{ext2} = 0 \quad (18)$$

Moreover, the position tracking of the master robot $\hat{X}_{m1}$ and slave robot $\hat{X}_{m2}$ should be similar, as follows,

$$\hat{X}_{m1} - \hat{X}_{m2} = 0 \quad (19)$$

This paper also deals with the construction of bilateral motion-scaling control with the use of modal space design provided by the calculation of the scaling Hadamard matrix [5], [4] as shown in Fig. 5. Suppose we want to reduce or increase the size of position and force response of slave robot. That is, we must specify how much to change the size along each dimension. The scaling for the force dimension does not have to be the same as the position dimension.

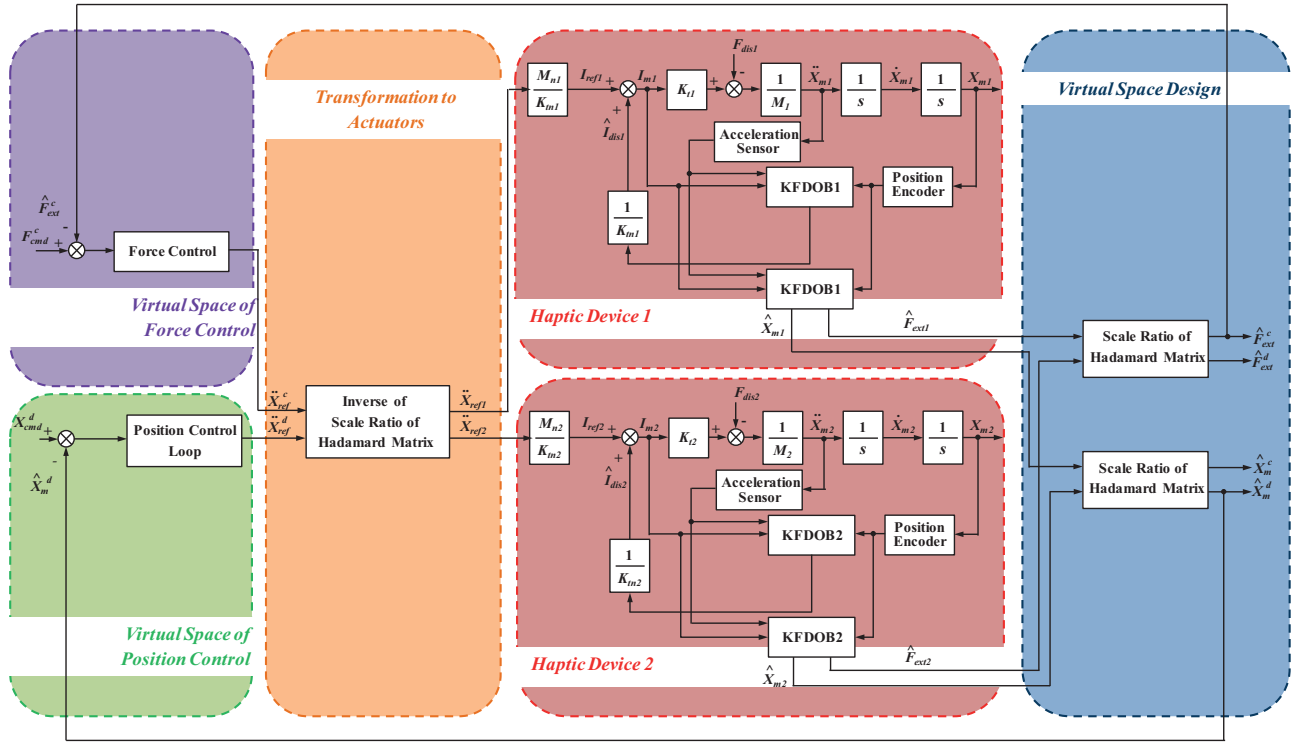


Fig. 5. Block diagram of the proposed bilateral motion-scaling control based on KFDOB.

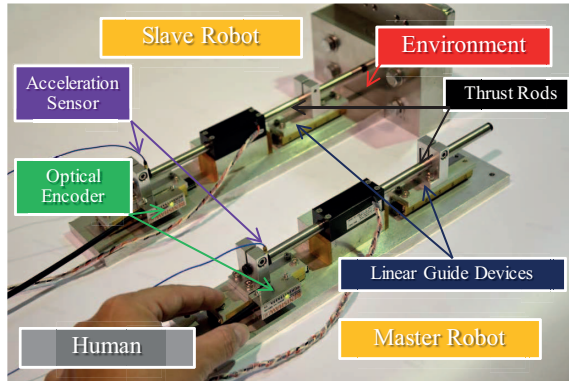


Fig. 6. Master-slave robot with multi-sensor fusion.

In order to reduce or magnify the force and position response of master-slave robot system, the scaling transformations are represented by using the scaling Hadamard matrix as follows,

$$\hat{F}_{ext1} + \alpha \hat{F}_{ext2} = 0 \quad (20)$$

$$\hat{X}_{m1} - \beta \hat{X}_{m2} = 0 \quad (21)$$

The force and position outputs have been scaled simply by multiplying each of its responses by the appropriate scaling factor in the force control α and the position control β .

Two control modes, namely the common mode and differ-

ential mode, are implemented and applied to control both the position and force. The underscript number 1 and 2 identify the master robot 1, and slave robot 2, respectively. In order to obtain information for the modal space design, the force estimation from the KFDOB at the master side, $\hat{F}_{ext1}$ and the KFDOB at the slave side, $\hat{F}_{ext2}$, are transformed into the virtual force in the common mode, $\hat{F}_{ext}^c$, and the differential mode, $\hat{F}_{ext}^d$, by using the scaling of Hadamard matrix based on the second order, H_2 . On the other hand, the position signals from the KFDOB at the master side, $\hat{X}_{m1}$, and the slave side, $\hat{X}_{m2}$, are also transformed into the virtual position in the common mode, $\hat{X}_m^c$, and the differential mode, $\hat{X}_m^d$, by using the H_2 . The virtual position of each mode is represented as follows:

$$\begin{bmatrix} \hat{F}_{ext}^c \\ \hat{F}_{ext}^d \end{bmatrix} = \begin{bmatrix} 1 & \alpha \\ 1 & -\beta \end{bmatrix} \begin{bmatrix} \hat{F}_{ext1} \\ \hat{F}_{ext2} \end{bmatrix} \quad (22)$$

$$\begin{bmatrix} \hat{X}_m^c \\ \hat{X}_m^d \end{bmatrix} = \begin{bmatrix} 1 & \alpha \\ 1 & -\beta \end{bmatrix} \begin{bmatrix} \hat{X}_{m1} \\ \hat{X}_{m2} \end{bmatrix} \quad (23)$$

The force control in the common mode can be separately analyzed as the proportional controller as shown in the following equation,

$$\ddot{X}_{ref}^c = (F_{cmd}^c - \hat{F}_{ext}^c) K_f \quad (24)$$

where F_{cmd}^c is the force command and K_f is the proportional gain of force control. $\ddot{X}_{ref}^c$ is the acceleration control signal in the common mode.

On the other hand, the position control in the differential mode can be analyzed as the proportional-derivative (PD) controller. The modal space designed of each mode is controlled in the acceleration dimension as follows,

$$\ddot{X}_{ref}^d = (X_{cmd}^d - \hat{X}_m^d)(K_p + sK_d) \quad (25)$$

where X_{cmd}^d is the position command. $\ddot{X}_{ref}^d$ is the acceleration control signal between the master and slave robot. According to the targets of the bilateral control, both force and position command were set as zero. K_p and K_d are the proportional gain and the derivative gain of position control, respectively.

In order to transform into the master robot and slave robot, the inverse of scaling hadamard matrix H_2^{-1} is applied. The transformation of acceleration control signals from modal space design to the real space in the master robot $\ddot{X}_{ref1}$ and slave robot $\ddot{X}_{ref2}$ are calculated as follows,

$$\begin{bmatrix} \ddot{X}_{ref1} \\ \ddot{X}_{ref2} \end{bmatrix} = \begin{bmatrix} \frac{\beta}{(\alpha+\beta)} & \frac{\alpha}{(\alpha+\beta)} \\ \frac{1}{(\alpha+\beta)} & \frac{-1}{(\alpha+\beta)} \end{bmatrix} \begin{bmatrix} \ddot{X}_{ref}^c \\ \ddot{X}_{ref}^d \end{bmatrix} \quad (26)$$

A robust control system is attained by applying the KFDOB. In addition, an acceleration control system is attained on robust interaction force control. Therefore, it is able to design the sensorless force control and position control in acceleration dimension independently by realizing the system based on common mode and differential mode.

V. EXPERIMENTAL RESULTS

The experimental setup of bilateral motion-scaling control consists of two set of haptic devices as shown in Fig. 6. The master-slave robots are controlled by a PC using RT-Linux with a sampling time of 100 μ s. The computer is equipped with analog output board, analog input board, and encoder-pulse counter board. All of the data from sensors as well as the controllers are written in the C language. The multi-sensor systems which consists of the optical linear encoder and acceleration sensor play a major role in control of the haptic device, by measuring the position and acceleration information. A non-contact optical linear encoder (RGH24 series; Renishaw) with high resolution grade of 0.1 μ m is used to read the scale in order to convert the encoded position into a digital square wave signal.

The mounting wax is used to mounted a piezoelectric acceleration sensors (NP-3211; Ono Sokki Technology, Inc.) on the master and slave robots, and applied to converts mechanical vibrations into analog signals. It offers a sensitivity of 1.02 mV with 1 m/s^2 . The frequency response range is provided from 1Hz to 10kHz.

The experiments were performed to evaluate the performance of the proposed approach with the human operators. The slave robot was commanded by the human operator at the master side to make contact with, and apply force to the high stiffness environment, which is an aluminum block, was

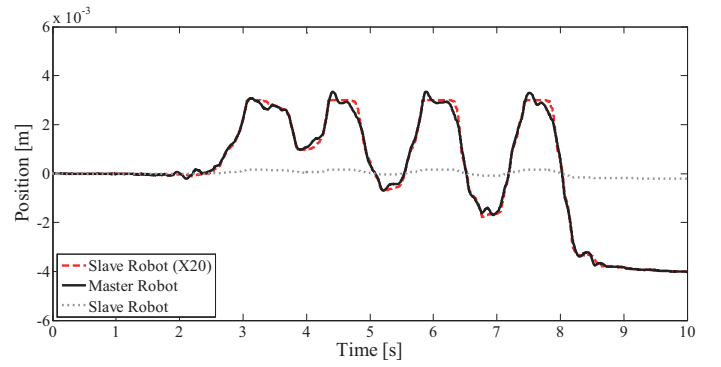


Fig. 7. Position response

used. User operates haptic device 1 (Master robot) at 2.0s. The period between 0.0s and 2.0s is a rest/transition period where no motion is produced. The scale ratio parameters of α and β are set as 20 in order to reduce the scaling of force and position of slave robot 20 times. The position responses at both master and slave sides are shown in Fig.7. The grey line and black line represent for the position response of slave and master robot, respectively. The red line represents for the position response of slave robot which is times by 20 in order to compare with the master robot side. As shown in the results, the position response of master side can be tracked almost identically over the position response of slave sides.

Fig. 8 and 9 show the experimental results of the value of action/reaction force responses by using the conventional and the proposed method, respectively. As shown in Fig. 9, the force response at the slave side sensed by the KFDOB is in opposite directions with respect to the force response at the master side sensed by the DOB. Fig. 10 and 11 show the experimental results of the value of velocity responses by using the conventional and the proposed method, respectively. From the experimental results, the DOB did not exhibit perfect transmission of the contact information to the master side, especially at the onset of the contact phase. When the impact force is performed beyond the frequency bandwidth of the DOB, which is based on only optical linear encoder, the force signals are distorted due to the cut-off frequency of the low-pass filter. By using the proposed method, the reaction response of master side can be tracked almost identically over the action response of slave sides. We analyze the force estimation by fast Fourier transform to obtain the frequency components of the estimated torque as shown in Fig. 12. Because the disturbance observer is deteriorated with a white Gaussian noise, the frequency components in the estimated action/reaction shown in Fig. 8 and 12 are undesired noise. After the slave robot is moved to contact the hard environment, the force feedback is transmitted to the master robot with very fast response and high bandwidth sensation. It is not necessary to modify parameter gains according to the stiffness of environment. The system is high robustness against the parameter variations, disturbance effects, and unknown environments.

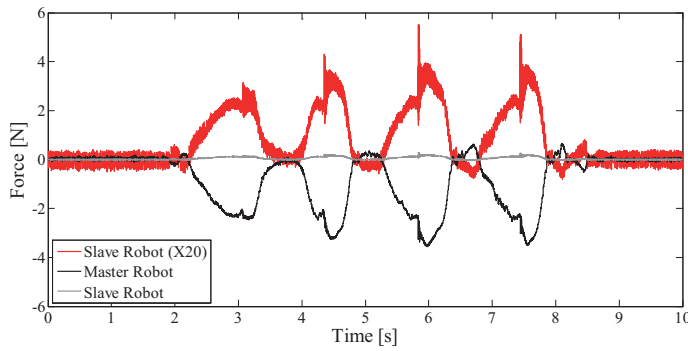


Fig. 8. Force response by using the conventional disturbance observer.

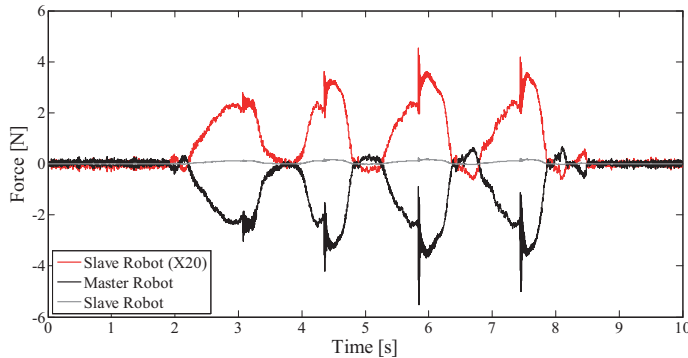


Fig. 9. Force response by using the proposed method

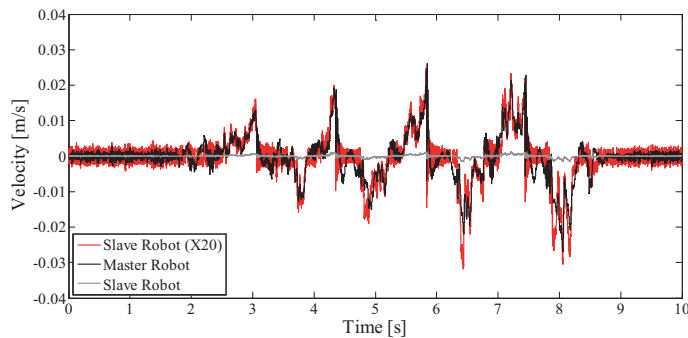


Fig. 10. Velocity response by using the conventional disturbance observer.

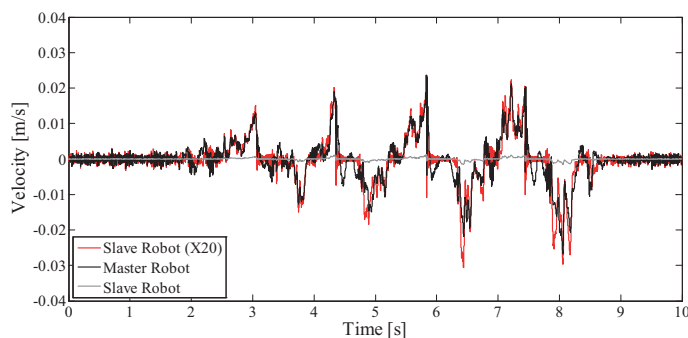


Fig. 11. Velocity response by using the proposed method

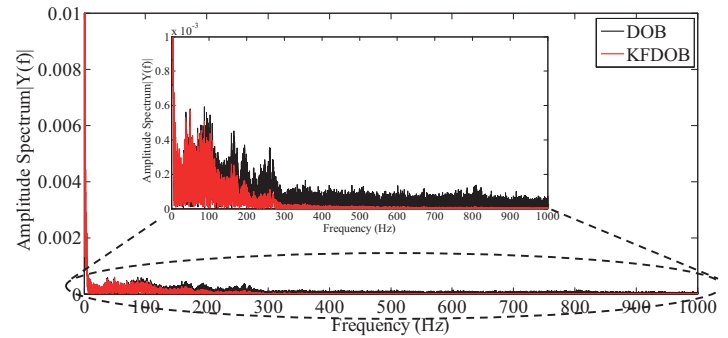


Fig. 12. FFT analysis of DOB and KFDOB.

VI. CONCLUSION

This paper proposes the bilateral motion-scaling control based on KFDOB to apply in the small size robot system. The scale ratio of Hadamard matrix is applied to reduce or magnify the force and position response of bilateral control. By using the proposed method, the position response of master side can be tracked almost identically over the position response of slave sides. After the slave robot is moved to contact the high stiffness environment, the force feedback is transmitted to the master robot with very fast response and high bandwidth sensation. Comparative experiments show the kalman-filter based disturbance observer and its multi-sensor fusion to provide performance superior to that of previously disturbance observer. As seen in the experimental results, it is clear that high transparency and good perception of the environmental stiffness with the response of the small scales of master-slave robot can be achieve successfully. An additional result of FFT analysis which guarantees noise compensation is also presented.

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Robotics-Assisted Rehabilitation Therapy for the Hands and Wrists Using Force Sensorless Bilateral Control with Shadow and Mirror Mode

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Abstract—Recently, the robotic devices are used mainly as therapy aids in the rehabilitation process of a disabled persons. The robotic device are designed with applications of techniques to support the adaptive exercise possible. It can apply to repeat the process exercise as many times as you wish. Moreover, the data measurements of their improvement or decline can be analyzed through the sensors on the device.

This paper proposes a specially designed force sensorless bilateral control based on Kalman-Filter Based State Observer (KFSO) for the hand and the wrist of the patient. By using KFSO, it can be applied to estimate a high bandwidth force sensation and good perception of an unknown environmental stiffness. Moreover, bilateral control based on the shadow mode and mirror mode is also proposed in order to improve human hand movement. To successfully implement neuro-recovery process, the mirror mode is proposed to help the brain into thinking the weaker hand or wrist is moving according to the stronger hand or wrist. With such a robust bilateral control scheme, significant high bandwidth haptic sensing in a rehabilitation robot can be achieved. The simulation results of the rehabilitation robot are provided to illustrate the performance of the proposed algorithms.

I. INTRODUCTION

Recently, the robot system are extending their capability to work in medical application such as remote surgery, exoskeletons for aiding limb or hand movement, autonomous wheelchair for disable people, treadmill training with partial body-weight support and rehabilitation process. Appropriate medical devices or robot systems have an important role for the rehabilitation process to support the exercise task which require close interaction between patient and doctor. The MIT-MANUS robotic arm use a performance-based progressive algorithm and embedded joint torque sensors to retrain motor movement of the limb for clinical neurological applications. Reference The finger-hand rehabilitation, namely AMADEO [1], has been proposed to improves the motor skills as well as the power of fingers or hand, and reduces spasticity by selecting passive, assistive and active variants from the different modules depending on the progress achieved in the course of therapy. The Bi-Manu Track [2] is developed to enable the bilateral practice of two distal movement cycles by offering different position and compliance control modes

for therapy. Recently, bimanual training is one of suggested rehabilitation technique to improve dexterity, grip strength and functional ability of the paretic limb [3]. It engages both limbs simultaneously in order to encourage the inter-limb coordination.

To successfully implement neuro-rehabilitation training process, the robot system also aims to aid recovery from a nervous system issues. Human-robot interaction and visual reality provide patients with an interactive way to improve mobility, perceptual skill development and strength.

The idea of functionality for a bilateral control system based on disturbance observer has been proposed to divide the system role into minimum components by [4]. The proposed method is implemented in the three parallel link manipulators with 3 DOF with twin drive systems. The contribution of this research is a robotics-assisted rehabilitation therapy for a wrist based on force sensorless bilateral control. A two-DOF rehabilitation robot is proposed and designed for active bilateral therapeutic exercises of the upper limb. In this paper, two bilateral control modes, namely the shadow mode and Mirror mode, are implemented and applied to control four AC servo motors synchronically in the same time according to the target of each modes. The shadow mode is implemented in the motor to support the movement of the patient in the same direction by using a simple bilateral control[5]. On the other hand, the mirror mode is applied to help the brain into thinking the weaker hand or wrist is moving according to the stronger hand or wrist. Moreover, the estimation of motor torque or force is obtained by applying Kalman-Filter Based State Observer (KFSO) [6]. A prototypical two-DOF with the proposed bilateral control is simulated and examined in order to illustrate the performance of the proposed algorithms.

II. MODEL OF THE ROBOTIC REHABILITATION SYSTEM

A two-DOF rehabilitation robot is designed for active bilateral therapeutic exercises of the upper limb as shown in Fig.1. Two AC servo motors are used to drive the robot system. The encoder attached to these motors can measure the angular position response. Arm supporter have been also implemented to fix the movement of the patient's arms. It can be easily

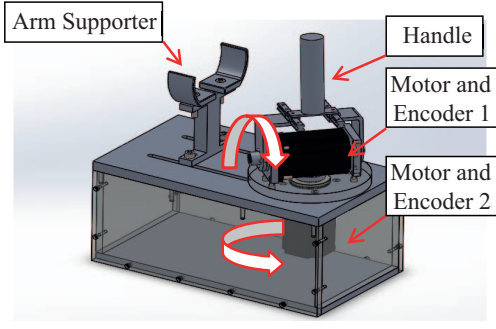


Fig. 1. A two-DOF rehabilitation robot for wrist orthopedic

adjusted the distance of the patient's arms. A model of the servo motor regulated under the ideal current source is shown in Fig. 2. From this figure, the dynamic model of the robot may be obtained in the following form

$$J\ddot{\theta}_m = K_t I_m - \left(\tau_f + D\dot{\theta}_m + \tau_{ext} + \Delta J\ddot{\theta}_m + \Delta K_t I_m \right) \quad (1)$$

$$\tau_l = \tau_f + D\dot{\theta}_m + \tau_{ext} \quad (2)$$

where, J denotes the motor inertia. θ_m , $\dot{\theta}_m$ and $\ddot{\theta}_m$ denote the angular position of motor, angular velocity of motor and angular acceleration of motor, respectively. K_t is the torque coefficient, and I_m is motor current. The load torque τ_l is the summation of friction torque τ_f , viscous friction $D\dot{\theta}_m$ and external torque τ_{ext} . The equation of the load torque is considered as (2). $\Delta J\ddot{\theta}_m$ is the variation torque due to changed inertia, $\Delta K_t I_m$ is the torque ripple due to space harmonics. The disturbance torque on the motor side τ_{dis} is defined as,

$$\tau_{dis} = \tau_f + D\dot{\theta}_m + \tau_{ext} + \Delta J\ddot{\theta}_m + \Delta K_t I_m \quad (3)$$

III. ESTIMATION OF ACTION/REACTION FORCE USING KALMAN-FILTER-BASED STATE OBSERVER (KFSO)

In recent years, a Kalman filter has been used extensively for a wide range of applications, such as signal processing and control applications. It is applied to estimate past, present and future state and generally used in sensor fusion and data fusion in order to combine the multiple measurements and generate the system's state at that time instant. The Kalman filter is an optimal recursive data processing algorithm that is based upon the process and measurement noise characteristics.

In this research, the action/reaction forces and motions of the master-slave robots can be estimated with the use of Kalman-Filter-Based State Observer (KFSO) [6]. In order to extract accurate of forces or torques on the robot, the nominal torque coefficient and the nominal motor inertia needs to be modeled and used in the observer. The model of the robot system can be formulated into the discrete state matrices as,

$$\begin{aligned} \mathbf{A} &= \begin{bmatrix} 1 & T_k & -\frac{T_k^2}{2J_n} \\ 0 & 1 & -\frac{T_k}{J_n} \\ 0 & 0 & 1 \end{bmatrix}, \mathbf{B} = \begin{bmatrix} 0 \\ \frac{K_{tn} T_k}{J_n} \\ 0 \end{bmatrix}, \quad (4) \\ \mathbf{C} &= \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \end{aligned}$$

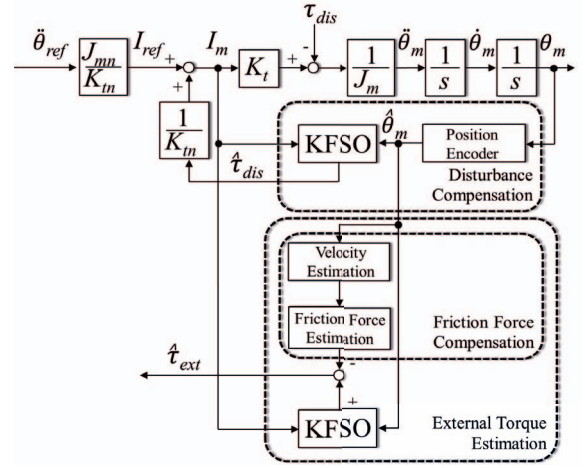


Fig. 2. Modeling of Servo Motor System with KFSO.

where T_k is a sampling time of the controller. The vector of states consists of angular position of motor, angular velocity of motor, and the external torque. The output disturbance torque $\hat{\tau}_{dis}$ is also updated by the input of motor current and angle position of motor as shown in Fig. 3 where we can think of $\frac{1}{K_{tn}}$ as a transfer function transforming disturbance torque to current. The estimation of disturbance force is used to compensate for unwanted disturbance that enter a system. Therefore, the system can be designed to follow the command input with small error.

A discrete sensor dynamics model can be formulated in the state space form as

$$\mathbf{x}_{(k+1)} = \mathbf{A}_{(k)}\mathbf{x}_{(k)} + \mathbf{B}_{(k)}\mathbf{u}_{(k)} + \mathbf{w}_{(k)} \quad (5)$$

$$\mathbf{z}_{(k)} = \mathbf{C}_{(k)}\mathbf{x}_{(k)} + \mathbf{v}_{(k)} \quad (6)$$

where k represents the sampling instant, $\mathbf{x}_{(k)} \in \mathfrak{R}^n$ is the vector of states, $\mathbf{u}_{(k)} \in \mathfrak{R}^m$ is the vector of input variables, $\mathbf{A}_{(k)} \in \mathfrak{R}^{n \times n}$ and $\mathbf{B}_{(k)} \in \mathfrak{R}^{n \times m}$ are system matrices, $\mathbf{C}_{(k)} \in \mathfrak{R}^{s \times n}$ is the measurement matrix, $\mathbf{z}_{(k)} \in \mathfrak{R}^s$ is the vector of measured variables, $\mathbf{w}_{(k)}$ is the process noise and $\mathbf{v}_{(k)}$ represents the measurement which is corrupted by white Gaussian noise.

It is assumed that the covariance matrix of the process noise $\mathbf{Q}$, the covariance matrices of the measurement noise $\mathbf{R}$ and the cross-covariance matrix are as given below:

$$\mathbf{Q} = E\{\mathbf{w}\mathbf{w}^T\} > 0 \quad (7)$$

$$\mathbf{R} = E\{\mathbf{v}\mathbf{v}^T\} \geq 0 \quad (8)$$

$$E\{\mathbf{w}\mathbf{v}^T\} = 0 \quad (9)$$

The Kalman filter bandwidth and its susceptibility to measurement noise depends on its covariance matrix of process noise $\mathbf{Q}$ and the covariance matrix of measurement noise $\mathbf{R}$. These values are used to tune the accuracy and response of the observer, and the matrices $\mathbf{Q}$ and $\mathbf{R}$ can be determined by using the simulations for the testing of the measurement sensors. A compromise between the performance of observer

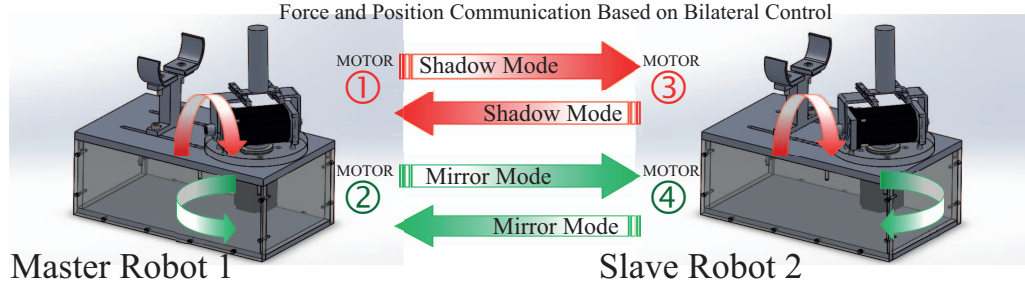


Fig. 3. Overview of the proposed bilateral control based on the shadow mode and mirror mode.

and the compensation of acceleration signal noise can be found.

The error covariance matrices $\mathbf{P}$ is the variance of the difference between the state and the measurements. The predicted equation which projects the current state estimate ahead in time are given by

$$\mathbf{x}_{(k|k-1)} = \mathbf{A}_{(k-1)}\mathbf{x}_{(k-1|k-1)} + \mathbf{B}_{(k-1)}\mathbf{u}_{(k-1)} \quad (10)$$

$$\mathbf{P}_{(k|k-1)} = \mathbf{A}_{(k-1)}\mathbf{P}_{(k-1|k-1)}\mathbf{A}_{(k-1)}^T + \mathbf{Q}_{(k-1)} \quad (11)$$

The Kalman filter gain matrix $\mathbf{M}$, that is based on the total uncertainty measurement of matrix $\mathbf{S}$ is computed by using the following equation

$$\mathbf{S}_{(k)} = \mathbf{C}_{(k)}\mathbf{P}_{(k|k-1)}\mathbf{C}_{(k)}^T + \mathbf{R}_{(k)} \quad (12)$$

$$\mathbf{M}_{(k)} = \mathbf{P}_{(k|k-1)}\mathbf{C}_{(k)}^T\mathbf{S}_{(k)}^{-1} \quad (13)$$

The estimated state vector and the error matrix are updated by an actual measurement $\bar{\mathbf{z}}_{(k)}$ of motion sensor at every sampling instant as follows

$$\mathbf{x}_{(k|k)} = \mathbf{x}_{(k|k-1)} + \mathbf{M}_{(k)}(\bar{\mathbf{z}}_{(k)} - \mathbf{C}_{(k)}\mathbf{x}_{(k|k-1)}) \quad (14)$$

$$\mathbf{P}_{(k|k)} = \mathbf{P}_{(k|k-1)} - \mathbf{M}_{(k)}\mathbf{S}_{(k)}\mathbf{M}_{(k)}^T \quad (15)$$

IV. BILATERAL CONTROL DESIGN BASED ON THE SHADOW MODE AND MIRROR MODE

Two rehabilitation robots are used to transfer the position and torque data between the master and slave side. Thus, four AC servo motors are controlled synchronically in the same time. The underscript number 1, 2, 3, and 4 identify the master robot 1, 2 and slave robot 3, 4 respectively as shown in Fig. 3. Two bilateral control modes, namely the shadow mode and Mirror mode, are implemented and applied to the rehabilitation robot system. The shadow mode is implemented in the motor 1 and 3. On the other hand, the mirror mode is applied to control the motor 2 and 4.

A. The Shadow Mode

Many efforts have been made in controlling master-slave robot to the same movement responses. In the mirror mode, a simple bilateral control is applied in this mode. The complexities that control of master-slave robots present are synchronization in terms of movements and torque. Master and slave robot must be controlled similarly. Thus, the target of the ideal bilateral control is to minimize the difference between

the force response in the master side $\hat{\mathbf{F}}_{ext1}$ and slave side $\hat{\mathbf{F}}_{ext3}$. We now write the equation of motion using Newton's law to sum to zero all of the forces as follows,

$$\hat{\mathbf{F}}_{ext1} + \hat{\mathbf{F}}_{ext3} = 0 \quad (16)$$

Moreover, the position tracking of the master robot $\hat{\mathbf{X}}_{m1}$ and slave robot $\hat{\mathbf{X}}_{m2}$ should be similar, as follows,

$$\hat{\mathbf{X}}_{m1} - \hat{\mathbf{X}}_{mw3} = 0 \quad (17)$$

B. The Mirror Mode

To successfully implement neurorehabilitation training process, the robot system also aims to aid recovery from a nervous system issues. Human-robot interaction and visual reality provide patients with an interactive way to improve mobility, perceptual skill development and strength. The mirror mode can be used to help the brain into thinking the weaker hand/wrist is moving according to the stronger hand/wrist. In the mirror mode, the reflection of movements of the slave robot must be controlled in the opposite in direction of the master robot. According to the robot movement, the desired target of the bilateral control may be achieve with the following control law,

$$\hat{\mathbf{F}}_{ext2} - \hat{\mathbf{F}}_{ext4} = 0 \quad (18)$$

Moreover, the position tracking of the master robot $\hat{\mathbf{X}}_{m1}$ and slave robot $\hat{\mathbf{X}}_{m2}$ should be similar amplitude but opposite in direction, as follows,

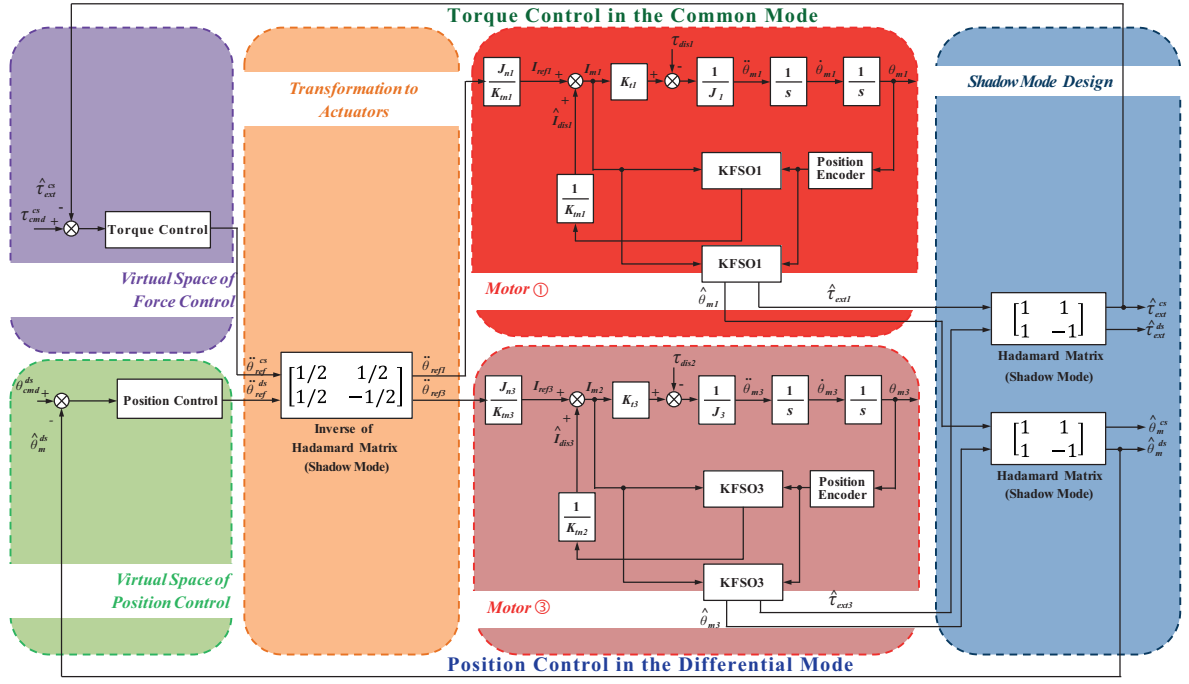
$$\hat{\mathbf{X}}_{m2} + \hat{\mathbf{X}}_{m4} = 0 \quad (19)$$

C. Controlling the Designed Targets Using Hadamard matrix

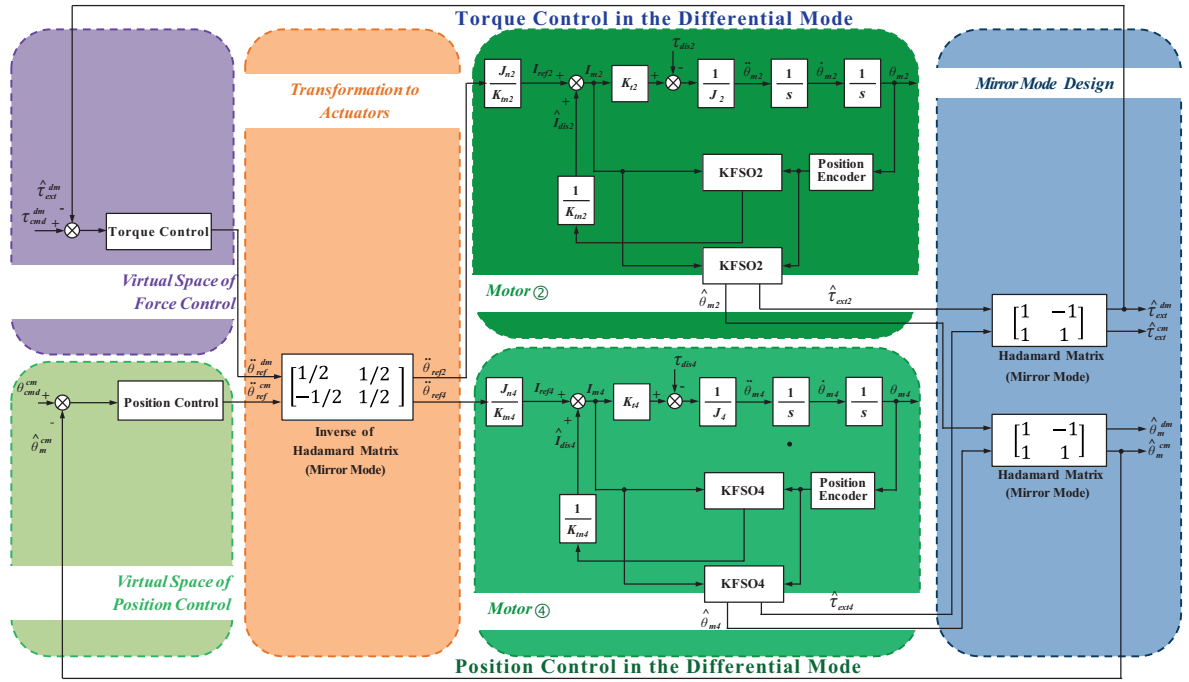
The bilateral control will modulate the angular position and torque to achieve the ideal target of bilateral control according to the mirror mode and shadow mode. Hadamard matrix based on the second order, $\mathbf{H}_2$ is used to transformed into the virtual space design [5]. The calculation of the Hadamard matrix in the shadow mode can be expressed as:

$$\begin{bmatrix} \hat{\tau}_{ext}^{cs} \\ \hat{\tau}_{ext}^{ds} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \hat{\tau}_{ext1} \\ \hat{\tau}_{ext3} \end{bmatrix} \quad (20)$$

$$\begin{bmatrix} \hat{\theta}_m^{cs} \\ \hat{\theta}_m^{ds} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \hat{\theta}_{m1} \\ \hat{\theta}_{m3} \end{bmatrix} \quad (21)$$



(a) Bilateral Control based on Shadow Mode



(b) Bilateral Control based on Mirror Mode

Fig. 4. Block diagram of the proposed multilateral control based on KFSO.

On the other hand, the calculation of Hadamard matrix in the mirror mode can be determined as:

$$\begin{bmatrix} \hat{\tau}_{ext}^{dm} \\ \hat{\tau}_{ext}^{cm} \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} \hat{\tau}_{ext2} \\ \hat{\tau}_{ext4} \end{bmatrix} \quad (22)$$

$$\begin{bmatrix} \hat{\theta}_m^{dm} \\ \hat{\theta}_m^{cm} \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} \hat{\theta}_{m2} \\ \hat{\theta}_{m4} \end{bmatrix} \quad (23)$$

The proposed bilateral control will modulate the angular position and torque to achieve the ideal target of bilateral

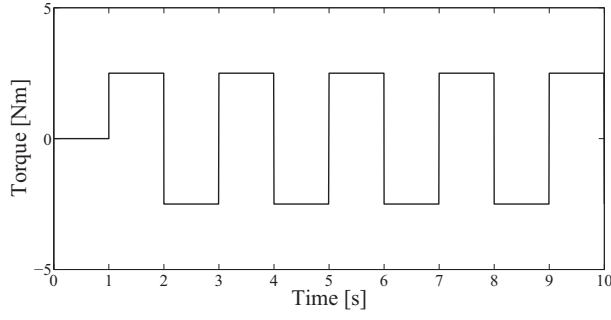


Fig. 5. Human external force

control. A simple PD controller is used to control angular position of motor and the P controller is applied to control torque of the motor as shown in the following equation, The Shadow Mode:

$$\ddot{\theta}_{ref}^{cs} = (\tau_{cmd}^{cs} - \hat{\tau}_{ext}^{cs}) K_f \quad (24)$$

$$\ddot{\theta}_{ref}^{ds} = (\theta_{cmd}^{ds} - \hat{\theta}_m^{ds})(K_p + sK_d) \quad (25)$$

The Mirror Mode:

$$\ddot{\theta}_{ref}^{dm} = (\tau_{cmd}^{dm} - \hat{\tau}_{ext}^{dm}) K_f \quad (26)$$

$$\ddot{\theta}_{ref}^{cm} = (\theta_{cmd}^{cm} - \hat{\theta}_m^{cm})(K_p + sK_d) \quad (27)$$

where τ_{cmd}^{cs} and τ_{cmd}^{dm} are the force command and K_f is the proportional gain of force control. θ_{cmd}^{ds} and θ_{cmd}^{cm} are the position command. K_p and K_d are the proportional gain and the derivative gain of position control, respectively. According to the targets of the bilateral control, both force and position command were set as zero.

In order to transform into the master robot and slave robot, the inverse of scaling hadamard matrix H_2^{-1} is applied. The transformation of acceleration control signals from modal space design to the real space in the master robot and slave robot are calculated as follows,

The Shadow Mode:

$$\begin{bmatrix} \ddot{\theta}_{ref1} \\ \ddot{\theta}_{ref3} \end{bmatrix} = \begin{bmatrix} 0.5 & 0.5 \\ 0.5 & -0.5 \end{bmatrix} \begin{bmatrix} \ddot{\theta}_{ref}^{cs} \\ \ddot{\theta}_{ref}^{ds} \end{bmatrix} \quad (28)$$

The Mirror Mode:

$$\begin{bmatrix} \ddot{\theta}_{ref2} \\ \ddot{\theta}_{ref4} \end{bmatrix} = \begin{bmatrix} 0.5 & 0.5 \\ -0.5 & 0.5 \end{bmatrix} \begin{bmatrix} \ddot{\theta}_{ref}^{dm} \\ \ddot{\theta}_{ref}^{cm} \end{bmatrix} \quad (29)$$

A robust control system is attained by applying the KFDOB. In addition, an acceleration control system is attained on robust interaction force control. Therefore, it is able to design the force sensorless bilateral control with shadow mode and mirror in acceleration dimension independently.

V. SIMULATION AND DISCUSSIONS

Various simulation results have been conducted to investigate the effectiveness of the controller performance. In this simulation, the designed controller is performed in Simulink

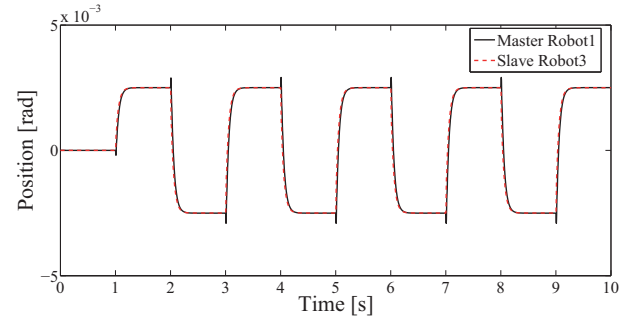


Fig. 6. Angular position response in the shadow mode

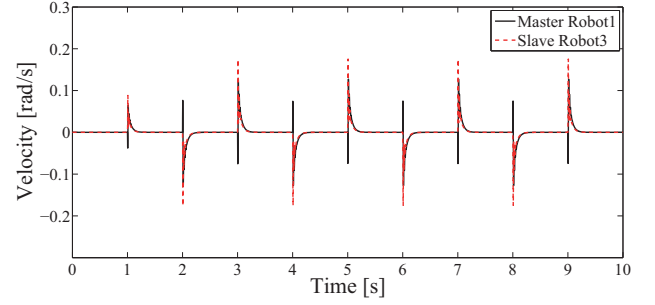


Fig. 7. Angular velocity response in the shadow mode

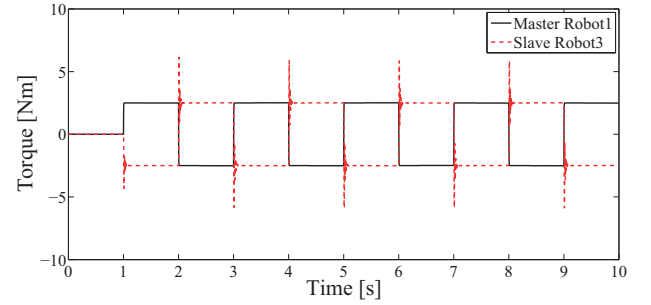


Fig. 8. Torque response in the shadow mode

MATLAB with the sampling time 0.0001 s. To model human hand at the slave side, the normal stiffness and damping values are set to 500 Nm/rad and 10 Nm-s/rad, respectively. The input pulse function as shown in Fig. 5 is applied as the external torque from human at the master side.

In the shadow mode, the angular position and velocity of the slave robot follows the response of the master robot closely because of the disturbance rejection as shown in Fig. 6 and 7, respectively. After the slave robot is moved, the force feedback in the opposite direction is transmitted to the master robot with very fast response and high bandwidth sensation as shown in Fig. 8.

In the mirror mode, similar parameters are also implemented with the simulation. Tracking results of the angular of position and velocity is depicted in Fig. 9 and 10, respectively. The movement response of master side can be tracked almost identically over the movement response of the slave sides.

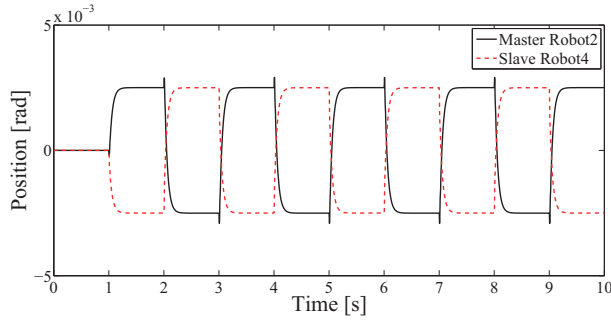


Fig. 9. Angular position response in the mirror mode

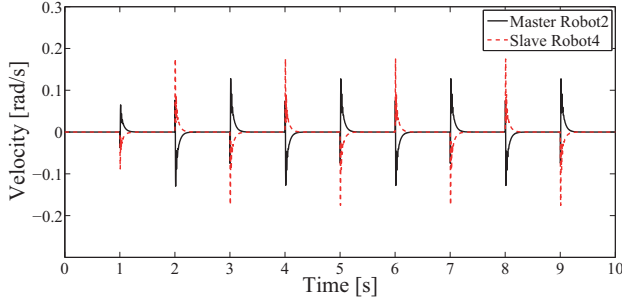


Fig. 10. Angular velocity response in the mirror mode

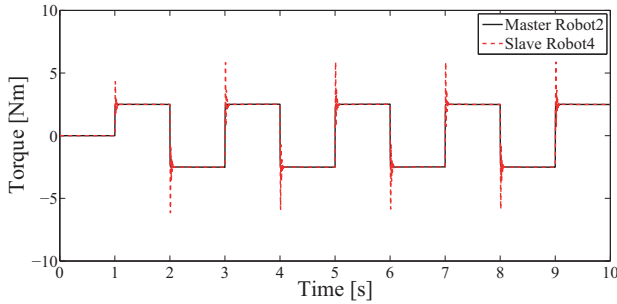


Fig. 11. Torque response in the mirror mode

Figure 11 displayed the estimated interaction force of the master-slave robots. The interaction torque of the slave robot tracks the external torque of the master robot faithfully. It is seen that the bilateral control which is designed for the mirror mode objective, may be used in the rehabilitation application as well.

VI. CONCLUSION

A prototypical system of a two-DOF rehabilitation robot is designed and analysed. The KFSO is employed to estimate the action/reaction force of master-slave robot. An advantage of Kalman filter is the ability to estimate state variable with noise compensation. Thus, these design techniques overcome limitation in the design of the conventional disturbance observer. Two modes bilateral control, namely the shadow mode and the mirror mode, are developed within the Hadamard matrix calculation. From the simulation results, the controller

TABLE I
PARAMETERS USED IN SIMULATION

Controller parameters	Symbol	Value	Units
Inertia moment of motor and load	J_n	0.106	$10^{-4} * kgm^2$
Torque coefficient	K_{tn}	0.327	Nm/A
Gain of torque control	K_f	4.3	
Proportional Gain of position control	K_p	1000	
Derivative Gain of position control	K_d	1500	



Fig. 12. A prototypical system of a master-slave rehabilitation robot

exhibits satisfactory results. The proposed controller is capable of regulating the output response according to the target of bilateral control. The desired target of the shadow mode and mirror mode is therefore accomplished. The tracking error is small enough for the rehabilitation process therefore the proposed rehabilitation robot system can be used for the actual application. In the future work, the real experimental set up as shown in Fig.12 will be examined and tested with the suggestions from the rehabilitation therapist.

ACKNOWLEDGMENT

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การลดการสั่นสะเทือนในหุ่นยนต์มาสเตอร์-สเลฟ ที่มีความยืดหยุ่นโดยวิธีการควบคุมอัตราส่วนการสั่นพ้อง จากวิธี แผนผังค่าสัมประสิทธิ์

Vibration Suppression of Flexible Master-Slave Robot Based on Resonance Ratio Control with Coefficient Diagram Method

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บทคัดย่อ

การสร้างแบบจำลองในการควบคุมมอเตอร์ผ่านภาระโหลดในเครื่องจักรกล หรือแขนกลอุตสาหกรรมที่มีความยืดหยุ่นที่ข้อต่อนั้นสามารถออกแบบ และ จำลองได้โดยใช้ระบบสองมวล (Two-Mass System) การนำระบบควบคุมแบบเก่า เช่น PID Controller มาประยุกต์ใช้อาจจะทำให้ได้ผลตอบสนองที่ไม่ดี เนื่องจากการสั่นสะเทือนจากโครงสร้างที่ยืดหยุ่น ดังนั้นการออกแบบตัวควบคุมแบบใหม่ที่มีความคงทนต่อการสั่นที่เกิดขึ้นจึงเป็นสิ่งสำคัญ ในบทความนี้นำเสนอแบบจำลองการควบคุมหุ่นยนต์แบบมาสเตอร์-สเลฟที่มีความยืดหยุ่นโดยใช้การควบคุมอัตราส่วนการสั่นพ้อง (Resonance Ratio Control) ที่มีการปรับค่าสัมประสิทธิ์จากวิธีแผนผังค่าสัมประสิทธิ์ (Coefficient Diagram Method : CDM) ร่วมกับ PID Controller จากการทดลองทางคณิตศาสตร์สรุปได้ว่า วิธีแบบใหม่ที่น่าเสนอสามารถขจัดสั่นสะเทือนในผลตอบสนองของแรงในโหมดร่วมกัน และลดข้อผิดพลาดการเคลื่อนที่ของหุ่นยนต์มาสเตอร์-สเลฟในโหมดต่างกัน

คำสำคัญ: ระบบสองมวล, การควบคุมอัตราส่วนการสั่นพ้อง, ตัวสังเกตแรงรบกวนหลายตัว, การควบคุมทั้งสองทาง, หุ่นยนต์มาสเตอร์-สเลฟ

Abstract

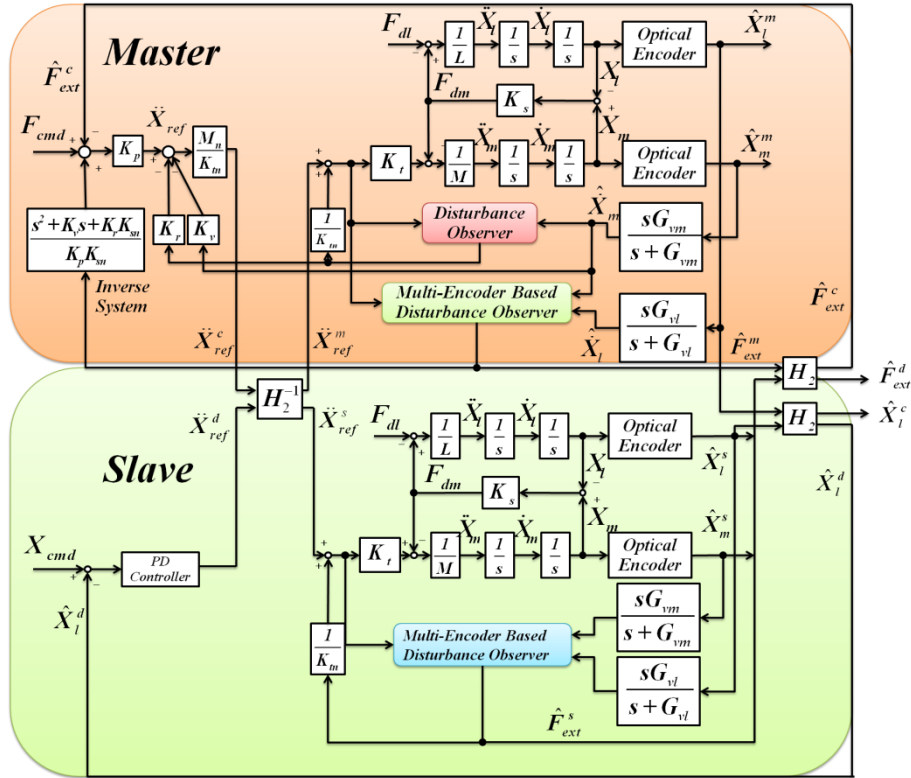
Generally, the industrial machine and robot manipulator can be modeled as the two-mass system. By using the conventional PID controller, this method cannot perform well due to the resonance in the system. Thus, it is necessary to design the controller that guarantees the robustness and suppress vibration. In this paper, a new method is proposed and applied to control the flexible master-slave robot by using the resonance ratio control with the Coefficient Diagram Method (CDM). The effectiveness of the proposed method is verified by numerical simulation results. By using the proposed method, the vibration on the system can be rejected very successfully in the force

response in the common mode. Moreover, the position error between both master and slave robot in the differential mode can be reduced.

Keywords: Two-mass System, Resonance ratio control, Multi-Encoder Disturbance Observer, Bilateral control, Master-Slave robot

1. บทนำ

ปัจจุบันระบบอัตโนมัติในเครื่องจักร และ หุ่นยนต์มีความสำคัญอย่างมากในอุตสาหกรรม การนำหุ่นยนต์มาประยุกต์ใช้งานแทนมนุษย์ หรือเครื่องมือทางการแพทย์ที่จำเป็นต้องมีการควบคุมตำแหน่งและแรงที่ถูกต้องแม่นยำ โดยทั่วไปการควบคุมแรงจะใช้เซ็นเซอร์แรงมาประยุกต์ในการวัดค่าแรงจากภายนอก และป้อนกลับเข้ามาคำนวณในระบบควบคุม แต่เซ็นเซอร์แรงจะมีข้อเสียคือ 1. ช่วงความถี่ (Bandwidth) ของเซ็นเซอร์แรงนั้นไม่สูงมากนัก และมีสัญญาณรบกวนในการควบคุม 2. ส่วนประกอบหลักของเซ็นเซอร์คือ สเตรนเกจ (strain gauge) ทำให้ออกแบบการควบคุมยากขึ้น เนื่องจากความยืดหยุ่นของสเตรนเกจ จึงต้องออกแบบการควบคุมให้มีการชดเชยผลกระทบที่เกิดจากการสั่น 3. เซ็นเซอร์แรงที่คุณภาพดีมีราคาสูง และสามารถวัดค่าแรงได้เฉพาะจุดที่เซ็นเซอร์แรงติดตั้งเท่านั้น งานวิจัยทางการควบคุมแรงที่ลดการสั่นในระบบสองมวลด้วยวิธีการควบคุมอัตราส่วนการสั่นพ้องถูกนำเสนอโดย Yuki [1] ต่อมา Mitsantisuk [2] ได้นำเสนอการประมาณค่าแรงที่ได้จากระบบสองมวลที่มีค่าแม่นยำมากขึ้น และใช้วิธีแผนผังค่าสัมประสิทธิ์ในการหาค่าสัมประสิทธิ์ที่ดีขึ้นในการควบคุมแรงด้วยวิธีการควบคุมอัตราส่วนการสั่นพ้อง ในบทความนี้จะนำเสนอแบบจำลองการควบคุมหุ่นยนต์แบบมาสเตอร์-สเลฟ ที่เป็นระบบสองมวล โดยใช้การควบคุมอัตราส่วนการสั่นพ้องที่มีการปรับค่าสัมประสิทธิ์จากวิธีแผนผังค่าสัมประสิทธิ์ร่วมกับ PID Controller ซึ่งวิธีนี้ทำให้สามารถส่งผ่านแรงจากฝั่งมาสเตอร์ไปยังสเลฟ ได้โดยลดการสั่นที่เกิดขึ้นในระบบ และให้ค่าที่ถูกต้องแม่นยำมากขึ้น และยังสามารถลดข้อผิดพลาดในการควบคุมตำแหน่งในหุ่นยนต์แบบมาสเตอร์-สเลฟได้ขึ้นด้วย



รูปที่ 1 การควบคุมแบบสองข้างพร้อมกัน Master-Slave

เมื่อ $\hat{F}_m$ และ $\hat{F}_s$ คือแรงจากฝั่งมาสเตอร์และฝั่งสเลฟ $\hat{X}_m$ และ $\hat{X}_s$ คือระยะทางจากฝั่งมาสเตอร์ และฝั่งสเลฟตามลำดับ

2.1 การประมาณค่าแรงจากภายนอก

ในบทความนี้ใช้ตัวสังเกตสัญญาณรบกวนจากเซ็นเซอร์หลายตัว (Multi-Encoder based Disturbance Observer : MEDOB) ในการประมาณค่าแรง โดยคำนวณจากค่ากระแส, ความเร็ว และตัวกรองความถี่ต่ำอันดับหนึ่งเป็นไปตามสมการดังที่ (3) และ (4) ซึ่งมีบล็อกไดอะแกรมดังรูปที่ 2

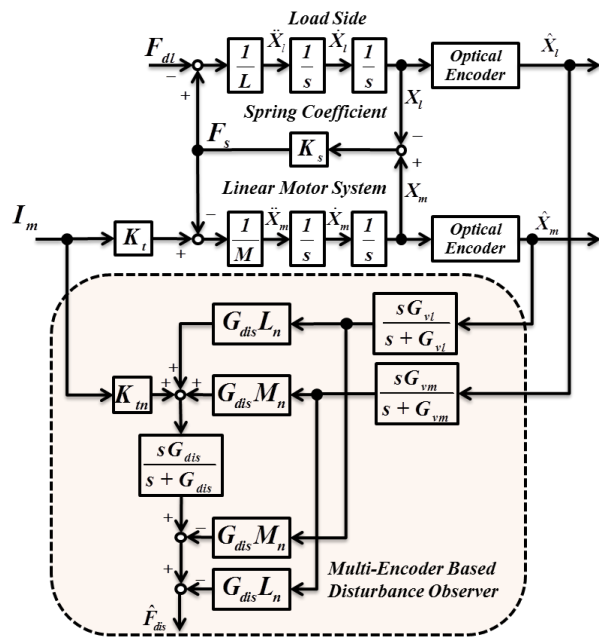
$$F_{dl} = K_{tn} I_m - M_n \ddot{X}_m - L \ddot{X}_l \quad (3)$$

$$\hat{F}_{dl} = \left(\frac{G_{mob}}{s + G_{mob}} \right) \left(K_{tn} I_m + G_{mob} M_n \hat{X}_m \right) + G_{mob} L_n \hat{X}_l - G_{mob} M_n \hat{X}_m - G_{mob} L_n \hat{X}_l \quad (4)$$

เมื่อ K_{tn} และ M_n คือ ค่าแรงและค่าน้ำหนักของมอเตอร์ที่ประมาณไว้ G_{dis} คือ ค่ากรองความถี่ต่ำของตัวสังเกตแรง G_{vm} คือ ค่ากรองความถี่ต่ำของการประมาณความเร็วมอเตอร์ G_{mob} คือ ค่ากรองความถี่ต่ำของตัวสังเกตสัญญาณรบกวนหลายตัวจากผลการทดลอง [2] การประมาณค่าแบบ MEDOB สามารถประมาณค่าแรงจากภายนอกได้ดีกว่าวิธีแบบ Disturbance Observer (DOB) และ Load Disturbance Observer (LDOB) โดยไม่จำเป็นต้องใช้สัมประสิทธิ์สปริง และเซ็นเซอร์แรงในการคำนวณ

2.2 การแบ่งโหมดการควบคุมด้วยเมตริกซ์ฮาดามาร์ด

เมตริกซ์ฮาดามาร์ด (Hadamard Matrix) คือ เมตริกซ์จัตุรัสที่มีค่าเป็น ± 1 และเป็นเมตริกซ์เชิงตั้งฉาก (Orthogonal matrix) ซึ่งถ้าเป็นเมตริกซ์ฮาดามาร์ดที่มีขนาด 2×2 จะทำให้แถวแรกของเมตริกซ์ถูกใช้เป็นโหมดร่วมกัน (Common mode) และแถวที่สองใช้เป็นโหมดต่างกัน

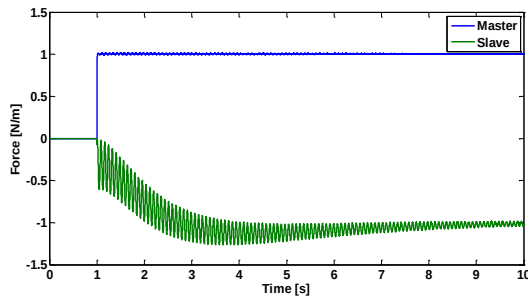


รูปที่ 2 Multi-Encoder Based Disturbance Observer

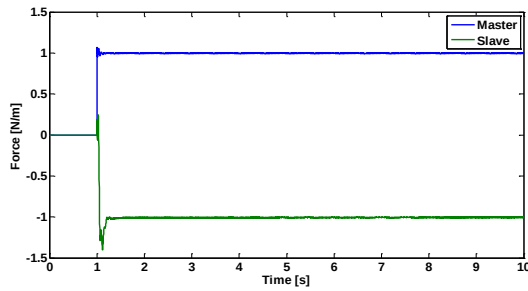
2. การควบคุมทั้งสองทิศทาง (Bilateral Control)

ในหุ่นยนต์มาสเตอร์-สเลฟ จะทำงานด้วยการควบคุมทั้งสองทิศทาง ซึ่งการควบคุมนี้นี้จะต้องเป็นไปตามกฎของนิวตัน กล่าวคือแรงกิริยาเท่ากับแรงปฏิกิริยา และระยะทางการเคลื่อนที่ของทั้งสองฝั่งจะต้องเท่ากัน [3] ดังที่ได้แสดงไว้ในที่ (1) และ (2)

$$\hat{F}_m + \hat{F}_s = 0 \quad (1) \quad \hat{X}_m - \hat{X}_s = 0 \quad (2)$$



(ก)



(ข)

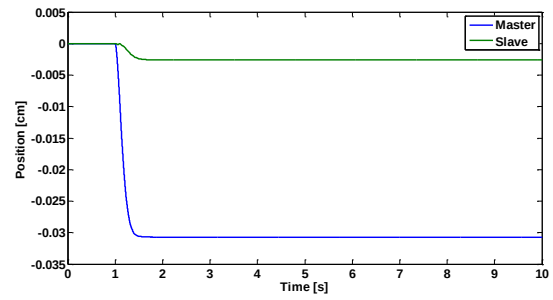
รูปที่ 5 เปรียบเทียบแรง

และฝั่งสเลฟ ที่นำมาเปรียบเทียบกันจะเป็นดังรูปที่ 5 รูปที่ 5.(ก) คือ กราฟที่ไม่มีการชดเชยค่าแรงที่ประมาณได้ รูปที่ 5.(ข) คือกราฟที่มีการชดเชยค่าแรงที่ประมาณได้กับเข้าระบบ พบว่าเมื่อมีการชดเชยให้กับระบบแล้วนอกจากลดการสั่นที่เกิดขึ้น เวลาได้ขึ้น(Rise time) ก็ลดลงด้วย และสามารถเข้าสู่ภาวะคงที่ได้เร็วกว่า ทำให้สามารถส่งค่าแรงที่ถูกต้องและแม่นยำ จากฝั่งมาสเตอร์มาที่ฝั่งสเลฟได้ จากการวัดตำแหน่งในการควบคุมแบบสองทิศทางจากทั้งฝั่งมาสเตอร์ และฝั่งสเลฟ นำมาเปรียบเทียบกันเป็นดังรูปที่ 6 รูป 6.(ก) คือ กราฟที่ไม่มีการชดเชยค่าแรงที่ประมาณได้เข้าสู่ระบบ ส่วนรูป 6.(ข) คือ กราฟที่มีการชดเชยค่าแรงที่ประมาณได้เข้าสู่ระบบ พบว่าทำให้สามารถลดข้อผิดพลาดในการเคลื่อนที่ของหุ่นยนต์ฝั่งสเลฟ เมื่อเทียบกับฝั่งมาสเตอร์ได้

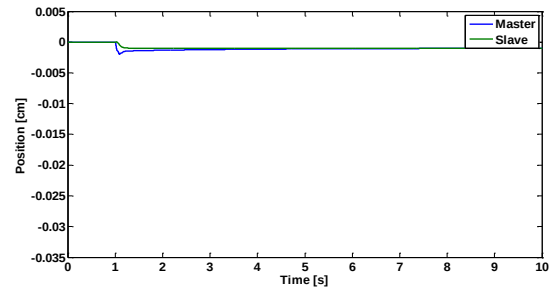
4. สรุป

การควบคุมแบบสองทิศทางในแบบจำลองหุ่นยนต์มาสเตอร์-สเลฟ ที่ควบคุมด้วยการควบคุมอัตราการสั่นพ้อง และใช้วิธีแผนผังค่าสัมประสิทธิ์ ทำให้สามารถส่งผ่านแรงจากฝั่งมาสเตอร์ไปฝั่งสเลฟได้ โดยลดการสั่นที่เกิดขึ้นในระบบทำให้ได้ค่าที่ถูกต้องแม่นยำมากขึ้น และสามารถลดข้อผิดพลาดในการควบคุมระยะทางหรือตำแหน่งในหุ่นยนต์แบบมาสเตอร์-สเลฟได้ดีขึ้น จากผลการทดลองนี้สามารถนำไปประยุกต์ใช้ในงานอุตสาหกรรมการกัดชิ้นงาน ที่มีการใช้หุ่นยนต์มาสเตอร์-สเลฟ หรือเครื่องมือแพทย์ที่ใช้ในการผ่าตัดส่วนที่อยากจะเข้าถึง และต้องการความละเอียดอ่อนที่จำเป็นต้องมีแรงสะท้อนกลับมา เพื่อช่วยในการควบคุมที่ดีขึ้น

5. กิตติกรรมประกาศ



(ก)



(ข)

รูปที่ 6 เปรียบเทียบตำแหน่ง

ขอขอบคุณสำนักงานกองทุนสนับสนุนการวิจัย (สกว.) ที่ให้การสนับสนุนทุนวิจัยหวังว่างานวิจัยนี้เป็นประโยชน์กับผู้ที่สนใจ และนักวิชาการที่จะนำงานวิจัยนี้ไปประยุกต์และพัฒนาระบบการควบคุมแรงให้ดีขึ้นต่อไป

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ชื่อ นายพลกร กลัดเจริญ กำลังศึกษาในระดับปริญญาโท ภาควิชาไฟฟ้า คณะวิศวกรรมศาสตร์ มหาวิทยาลัยเกษตรศาสตร์ งานวิจัยที่สนใจ ด้านการควบคุมแรง

การควบคุมอัตราส่วนย่อ/ขยายแบบสองทิศทางโดยใช้ตัวสังเกตการณ์สัญญาณรบกวน

จากตัวกรองคาลมานสำหรับอุปกรณ์การแพทย์

Macro/Micro Bilateral Control Based on Kalman-Filter Based State Observer for Medical Device

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บทคัดย่อ

ระบบหุ่นยนต์เป็นเครื่องมือที่มีประสิทธิภาพสูงที่มีประโยชน์ในการประยุกต์ใช้งานทางการแพทย์และอุตสาหกรรม แต่การนำเซนเซอร์วัดแรงมาใช้นั้นเกิดปัญหาในเรื่องข้อจำกัดในการควบคุมแรง บทความฉบับนี้นำเสนอการออกแบบระบบควบคุมแบบสองทิศทางแบบใหม่ โดยใช้ตัวสังเกตการณ์สัญญาณรบกวน KFSSO ซึ่งสามารถนำมาประยุกต์ใช้ให้เกิดประสิทธิภาพสูงในการส่งข้อมูล มีแรงสัมผัสที่ดีต่อสภาพแวดล้อม นอกจากนี้อัตราส่วนของ เมทริกซ์ Hadamard ยังได้ถูกนำเสนอเพื่อปรับอัตราส่วนของผลตอบสนองของตำแหน่งและแรงอีกด้วย คำสำคัญ: การควบคุมสองทิศทาง, การประมาณค่าแรงภายนอก, ตัวกรองคาลมาน

Abstract

Robotic system is a high performance tool that offers distinct advantages in medical and industrial application. However, the drawback due to the use of force sensor presents a limitation in the force control. This paper proposes a specially designed bilateral control based on KFSSO that can be applied to obtain a high transparency and good perception of an unknown environmental stiffness. Moreover, the ratio gain of Hadamard matrix is also analyzed in order to transform the scaling of force and position response

Keywords: bilateral control, external force estimation, kalman filter

1. บทนำ

ในปัจจุบันมีการนำหุ่นยนต์มาใช้ในโรงงานอุตสาหกรรมเป็นจำนวนมากเพื่อช่วยในการเพิ่มผลผลิตของสินค้า รวมถึงการช่วยปรับปรุงคุณภาพของสินค้าให้ดียิ่งขึ้น กระบวนการผลิตดังกล่าวเป็นการทำงานแบบซ้ำๆ ในพื้นที่ปิด ดังนั้นคุณสมบัติที่สำคัญในหุ่นยนต์ประเภทนี้ ได้แก่ มีความถูกต้องแม่นยำ มีความรวดเร็วสูง และต้องคุ้มค่าแก่การลงทุน การนำหุ่นยนต์มาประยุกต์ใช้เพื่อช่วยเหลือการทำงานของมนุษย์มีแนวโน้มความต้องการที่สูงมากยิ่งขึ้นในอนาคต หุ่นยนต์ดังกล่าวจะนำมาใช้ในพื้นที่

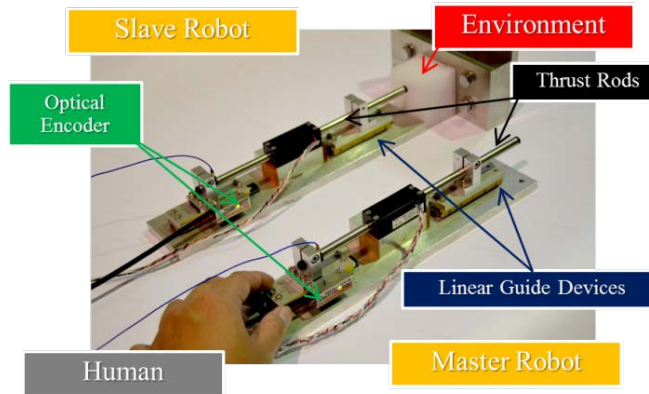
บริเวณกว้าง และสามารถสัมผัสกับสิ่งแวดล้อมแบบเปิดที่มีการเปลี่ยนแปลงได้ตลอดเวลา คุณสมบัติที่สำคัญในหุ่นยนต์ประเภทนี้ได้แก่ มีความปลอดภัย และมีลักษณะภายนอกที่เป็นมิตรกับมนุษย์ ดังนั้นการออกแบบระบบควบคุมแบบเก่าที่ใช้ในหุ่นยนต์อุตสาหกรรมจึงไม่เหมาะสมสำหรับการประยุกต์ใช้งานกับมนุษย์

การออกแบบระบบควบคุมสมัยใหม่จึงจำเป็นต้องออกแบบให้สอดคล้องกับการสัมผัสกับสิ่งแวดล้อมภายนอก เมื่อพิจารณาจากสภาพแวดล้อมภายนอกจะเห็นได้ว่ามีมิติการสัมผัสที่ไม่จำกัด ในทางกลับกันระบบหุ่นยนต์มีองศาอิสระ Degree of freedom (DOF) ที่จำกัดตามโครงสร้างที่ออกแบบ ระบบควบคุมจึงควรจะสามารถแสดงข้อมูลของสิ่งแวดล้อมโดยใช้ค่าจากเซนเซอร์ และตัวแปรภายในของระบบหุ่นยนต์เองเพื่อนำระบบหุ่นยนต์ไปใช้งานกับมนุษย์ระบบควบคุมแรงได้ถูกนำเสนอและประยุกต์ใช้ในหลายงานวิจัย ระบบควบคุมแรงดังกล่าวมีพื้นฐานจากการพัฒนามาจากเซนเซอร์วัดแรงทั้งสิ้น [1] เนื่องจากว่าเซนเซอร์วัดแรงนั้นมีช่วงความถี่ (Bandwidth) ที่ไม่ได้สูงมากนักและยังมีสัญญาณรบกวนเข้ามารบกวน (Noise) [2] ในระบบควบคุม ดังนั้นจึงทำให้ประสิทธิภาพของระบบควบคุมไม่เพียงพอต่อการนำมาใช้งานบางประเภท ที่ต้องการการส่งผ่านแรงป้อนกลับที่มีความถูกต้องและมีความถี่สูง งานวิจัยฉบับนี้นำเสนอวิธีการใหม่ในการนำประโยชน์จากข้อมูลที่ได้จากสิ่งแวดล้อมภายนอกมาใช้ประมาณค่าแรงภายนอก และนำมาประยุกต์ใช้กับระบบควบคุมทั้งสองทิศทางโดยที่ไม่จำเป็นต้องใช้เซนเซอร์วัดแรง นอกจากนี้ยังนำเสนอวิธีการในการเทียบอัตราส่วนแรง และตำแหน่ง เพื่อใช้ในการประยุกต์ใช้กับชิ้นงานที่มีขนาดเล็กมากอีกด้วย

2. แบบจำลองของหุ่นยนต์เพื่อช่วยในการส่งผ่านแรงสัมผัส

2.1 มอเตอร์เชิงเส้น (Linear Shaft Motor)

ส่วนประกอบหลักที่สำคัญในการออกแบบหุ่นยนต์เพื่อช่วยในการส่งผ่านแรงสัมผัส ได้แก่ มอเตอร์เชิงเส้น (Linear Shaft Motor) กลไกช่วยการเคลื่อนที่ และ เซนเซอร์ที่ใช้ในการวัดการเคลื่อนที่ดังที่ได้แสดงในรูปที่ 1 โดยระบบของเซนเซอร์ประกอบด้วย เอนโคเดอร์แบบ Optical ใช้ในการวัดค่าตำแหน่ง มอเตอร์เชิงเส้นจะนำมาใช้ทั้งหมด 2 ชุด ได้แก่ฝั่ง Master Robot นำมาใช้ควบคุมการเคลื่อนที่โดยผู้ใช้งาน และ



รูปที่ 1 ส่วนประกอบของหุ่นยนต์เพื่อใช้ในระบบควบคุมสองทิศทาง Slave Robot นำมาใช้ในการสัมผัสกับสิ่งแวดล้อมภายนอก แบบจำลองของมอเตอร์เชิงเส้นที่ควบคุมการเคลื่อนที่โดยการเปลี่ยนแปลงของกระแสไฟฟ้าสามารถแสดงได้ดังรูปที่ 2 จากรูปดังกล่าวสมการพลศาสตร์ของมอเตอร์สามารถคำนวณได้ดังต่อไปนี้

$$M\ddot{X}_m = K_t I_m - (F_f + D\dot{X}_m + F_{ext} + \Delta M\ddot{X}_m + \Delta K_t I_m) \quad (1)$$

$$F_l = F_f + D\dot{X}_m + F_{ext} \quad (2)$$

โดยที่ M คือค่ามวลของมอเตอร์ X_m , $\dot{X}_m$ และ $\ddot{X}_m$ คือค่าตำแหน่ง ความเร็ว และความเร่งของมอเตอร์ตามลำดับ K_t คือค่าคงที่โมเมนต์แรงบิดของมอเตอร์ และ I_m คือค่ากระแสของมอเตอร์ ค่าโหลดของแรง F_l คือผลรวมของค่าแรงเสียดทาน F_f ค่าแรงเสียดทานที่เกิดจากความเร็ว $D\dot{X}_m$ และค่าแรงจากภายนอก F_{ext} ค่า $\Delta M\ddot{X}_m$ คือค่าความผันแปรของแรงบิดที่เกิดจากการเปลี่ยนแปลงมวล $\Delta K_t I_m$ คือค่าแรงที่กระทำเนื่องจากการฮาร์โมนิก ค่าสัญญาณรบกวนของแรง F_{dis} ในฟังก์ชันของมอเตอร์สามารถนิยามได้จาก

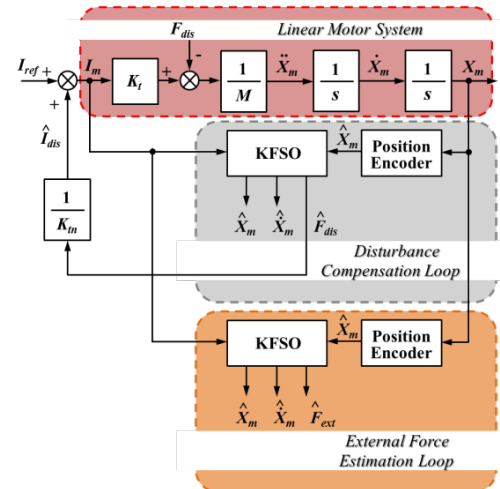
$$F_{dis} = F_f + D\dot{X}_m + F_{ext} \Delta M\ddot{X}_m + \Delta K_t I_m \quad (3)$$

2.2 การประมาณค่าแรงภายนอกโดยไม่จำเป็นต้องใช้เซนเซอร์วัดแรง

ในงานวิจัยนี้ได้นำเสนอวิธีการใหม่ในการประมาณค่าแรง โดยใช้ Kalman filter ในรูปที่ 2 แสดงถึงโครงสร้างของตัวสังเกตการณ์สัญญาณรบกวนโดยใช้ตัวกรองสัญญาณคาลมาน Kalman filter (Kalman Filter based State Observer, KFSSO) สมการของ Kalman filter สามารถคำนวณได้ในรูปแบบเมทริกซ์สถานะดังต่อไปนี้

$$A = \begin{bmatrix} 1 & T_k & \frac{-T_k^2}{2M_n} \\ 0 & 1 & \frac{-T_k}{M_n} \\ 0 & 0 & 1 \end{bmatrix}, B = \begin{bmatrix} 0 \\ \frac{K_{tn}T_k}{M_n} \\ 0 \end{bmatrix}, C = [1 \quad 0 \quad 0] \quad (4)$$

สัญญาณขาเข้าของตัวสังเกตการณ์คือค่ากระแสไฟฟ้า และความเร็วของมอเตอร์โดยที่ T_k คือค่าเวลาการสุ่มตัวอย่าง (Sampling time) ของคอนโทรลเลอร์จากสมการดังกล่าว ค่าที่ประมาณออกมาได้คือค่าตำแหน่ง ความเร็ว และค่าแรงภายนอกนั้นต้องใช้ค่าตัวแปรมวลของมอเตอร์ M_n และ ค่าคงที่โมเมนต์แรงบิดของมอเตอร์ K_{tn} ในการคำนวณ ซึ่ง



รูปที่ 2 แบบจำลองมอเตอร์และการประมาณค่าแรงภายนอกโดย KFSSO สามารถหาได้จากข้อมูลของผู้ผลิตมอเตอร์ สมการของ Kalman filter สามารถคำนวณได้ในรูปแบบ state space form ดังต่อไปนี้

$$x_{(k+1)} = A_{(k)}x_{(k)} + B_{(k)}u_{(k)} + w_{(k)} \quad (5)$$

$$z_{(k)} = C_{(k)}x_{(k)} + v_{(k)} \quad (6)$$

โดยที่ค่า k คือค่าอัตราการสุ่ม $x_{(k)}$ คือ เวกเตอร์ของสถานะ $u_{(k)}$ คือ เวกเตอร์ของสัญญาณตัวแปรขาเข้า $A_{(k)}$ และ $B_{(k)}$ คือเมทริกซ์ของระบบ $C_{(k)}$ คือเมทริกซ์การวัด $z_{(k)}$ คือ เวกเตอร์ของตัวแปรที่วัดได้ $w_{(k)}$ คือ กระบวนการประมวลผลค่าสัญญาณรบกวน และ $v_{(k)}$ คือการวัดซึ่งถูกรบกวนโดยสัญญาณรบกวน white Gaussian noise โดยสมมุติเมทริกซ์ covariance ของกระบวนการประมวลผลค่าสัญญาณรบกวน Q เมทริกซ์ covariance ของการวัดสัญญาณรบกวน R และ เมทริกซ์ cross-covariance ได้จากสมการดังนี้

$$Q = E\{ww^T\} > 0 \quad (7)$$

$$R = E\{vv^T\} > 0 \quad (8)$$

$$E\{ww^T\} = 0 \quad (9)$$

ขอบเขตของความถี่ของ Kalman filter และความอ่อนไหวต่อการวัดสัญญาณรบกวนขึ้นอยู่กับเมทริกซ์ Q และ R ค่านี้จะใช้ในการปรับความถูกต้องแม่นยำ และผลตอบแทนของตัวสังเกตการณ์ให้เหมาะสม ค่าความผิดพลาดของเมทริกซ์ covariance P คือค่าการเปลี่ยนแปลงของความแตกต่างระหว่างสถานะและการวัด สมการการทำนายสถานะล่วงหน้าของค่าประมาณปัจจุบันคำนวณได้โดย

$$x_{(k|k+1)} = A_{(k-1)}x_{(k-1|k-1)} + B_{(k-1)}u_{(k-1)} \quad (10)$$

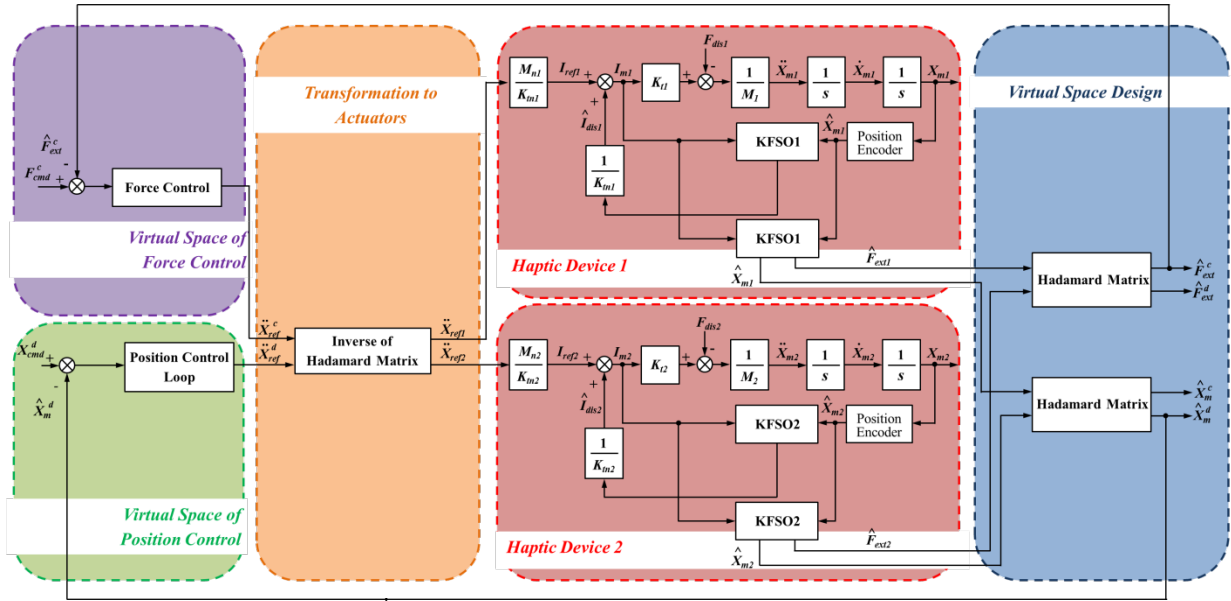
$$P_{(k|k+1)} = A_{(k-1)}P_{(k-1|k-1)}A_{(k-1)}^T + Q_{(k-1)} \quad (11)$$

$M_{(k)}$ คือค่าเมทริกซ์เกนของ Kalman filter ซึ่งพิจารณาจากเมทริกซ์ผลรวมของความไม่แน่นอนในการวัด $S_{(k)}$ สามารถคำนวณได้จากสมการดังต่อไปนี้

$$S_{(k)} = C_{(k)}P_{(k|k-1)}C_{(k)}^T + R_{(k)} \quad (12)$$

$$M_{(k)} = P_{(k|k-1)}C_{(k)}^T S_{(k)}^{-1} \quad (13)$$

การประมาณค่าเวกเตอร์สถานะและ ค่าความผิดพลาดของเมทริกซ์จะปรับข้อมูลให้เป็นปัจจุบันโดยการนำค่าจากการวัดจริงโดยใช้



รูปที่ 3 โครงสร้างของระบบควบคุมสองทิศทางแบบย่อ/ขยาย อัตราส่วน

เซนเซอร์เอนโคเดอร์ และ เซนเซอร์ความเร่งในทุกช่วงเวลา
 ดังนี้

$$x_{(k|k)} = x_{(k|k-1)} + M_{(k)} (\bar{z}_{(k)} - C_{(k)} x_{(k|k-1)}) \quad (14)$$

$$P_{(k|k)} = P_{(k|k-1)} - M_{(k)} S_{(k)} M_{(k)}^T \quad (15)$$

โดยค่า $1/K_{cn}$ นำมาใช้ป้อนกลับเพื่อชดเชยการผันผวนจากภายนอก

3. โครงสร้างของระบบควบคุมแรงสัมผัสเพื่อช่วยรวมการทำงานระหว่างมนุษย์และหุ่นยนต์

การควบคุมแบบสองทิศทาง (Bilateral control) นั้นมีประโยชน์อย่างยิ่งในการส่งผ่านประสบการณ์การสัมผัส ผู้ใช้งานสามารถให้หุ่นยนต์จากฝั่ง Master ควบคุมการเคลื่อนที่ของหุ่นยนต์ฝั่ง Slave และแรงที่กระทำกับสิ่งแวดล้อมจากหุ่นยนต์ฝั่ง Slave นั้นสามารถป้อนกลับมายังผู้ใช้งานได้โดยผ่านหุ่นยนต์ฝั่ง Master ตามกฎแห่งกิริยาและปฏิกิริยาของนิวตัน (Newton law of action and reaction) คือแรงที่วัตถุหนึ่งกระทำต่อวัตถุที่สองย่อมเท่ากับแรงที่วัตถุที่สองกระทำกับอีกวัตถุหนึ่ง แต่ทิศทางตรงกันข้าม และการเคลื่อนที่ของตำแหน่งมีทิศทางเดียวกัน ดังนั้นเป้าหมายในการออกแบบระบบควบคุมแรงคือการลดค่าความแตกต่างระหว่างผลตอบสนองของแรงสัมผัสระหว่างหุ่นยนต์ฝั่ง Master F_{ext1} และ Slave F_{ext2}

$$F_{ext1} + F_{ext2} = 0 \quad (16)$$

นอกจากนี้เป้าหมายของการออกแบบระบบควบคุมตำแหน่งคือการทำให้ผลตอบสนองของการเคลื่อนที่ของหุ่นยนต์ทั้งสองฝั่ง X_{m1} , X_{m2} มีค่าที่เท่ากัน

$$X_{m1} = X_{m2} \quad (17)$$

จากเป้าหมายในการออกแบบระบบควบคุมดังกล่าว จึงสามารถแบ่งโหมดการควบคุมได้สองส่วนนั่นคือ โหมดการควบคุมที่ร่วมกัน (Common mode) และ โหมดการควบคุมที่ต่างกัน (Differential mode) โดยโหมดการควบคุมที่ร่วมกันนั้นใช้ในการควบคุมตำแหน่ง และ โหมดการควบคุมที่

ต่างกันนั้นใช้ในการควบคุมแรงของทั้งหุ่นยนต์ Master และ Slave ในระบบควบคุมแบบเกาออกแบบ โดยการควบคุมความเร็วในลูปภายใน (Inner loop) และควบคุมแรงด้วยลูปภายนอก (Outer loop) ในทางกลับกัน ระบบควบคุมแบบใหม่นี้จะนำเสนอนั้นจะใช้ Hadamard metrics S_2 ในการเปลี่ยนค่าตำแหน่งของมอเตอร์ X_{m1}, X_{m2} และแรงสัมผัสจากผลตอบสนองของมอเตอร์ F_{ext1}, F_{ext2} ไปสู่การควบคุมในมิติของตำแหน่งเสมือนร่วม X_m^c เสมือนต่าง X_m^d และ ผลตอบสนองของแรงเสมือนร่วม F_{ext}^c , เสมือนต่าง F_{ext}^d และควบคุมทั้งสองโหมดในเวลาเดียวกันดังที่ได้แสดงในรูปที่ 3 และสามารถคำนวณสมการได้ดังต่อไปนี้

$$\begin{bmatrix} F_{ext}^c \\ F_{ext}^d \end{bmatrix} = \begin{bmatrix} 1 & \alpha \\ 1 & -\beta \end{bmatrix} \begin{bmatrix} F_{ext1} \\ F_{ext2} \end{bmatrix} = S_2 \begin{bmatrix} F_{ext1} \\ F_{ext2} \end{bmatrix} \quad (18)$$

$$\begin{bmatrix} X_m^c \\ X_m^d \end{bmatrix} = \begin{bmatrix} 1 & \alpha \\ 1 & -\beta \end{bmatrix} \begin{bmatrix} X_{m1} \\ X_{m2} \end{bmatrix} = S_2 \begin{bmatrix} X_{m1} \\ X_{m2} \end{bmatrix} \quad (19)$$

ในงานวิจัยนี้ได้นำเสนอวิธีการใหม่ในการกำหนดค่าอัตราส่วนย่อ/ขยายแรงและตำแหน่งโดยที่ α, β คือค่าอัตราส่วนที่ต้องการย่อ/ขยายของแรง และตำแหน่งตามลำดับ โหมดการควบคุมทั้งสองสามารถทำการวิเคราะห์แยกออกจากกันได้ โดยในที่นี้จะใช้โหมดการควบคุมที่ต่างกันในการควบคุมตำแหน่งด้วย Proportional-derivative controller

$$\ddot{X}_{ref}^d = (\dot{X}_{cmd}^d - \dot{X}_m^d)(K_p + sK_d) \quad (20)$$

โดยที่ค่า $\dot{X}_{ref}^d$ คือค่าความเร่งในโหมดความแตกต่าง $\dot{X}_{cmd}^d$ คือค่าคำสั่งตำแหน่งที่ต้องการใน โหมดความแตกต่าง K_p คือค่า Proportional เกนของการควบคุมตำแหน่ง และ K_d คือค่า Derivative เกนของการควบคุมตำแหน่ง สำหรับ โหมดการควบคุมที่ร่วมกันนั้นใช้สำหรับการควบคุมแรงด้วย Derivative controller

$$\ddot{X}_{ref}^c = (F_{cmd}^c - F_{ext}^c)K_f \quad (21)$$

โดยที่ค่า $\ddot{X}_{ref}^c$ คือค่าความเร่งในโหมดความเหมือนร่วม F_{cmd}^c คือค่าคำสั่งแรงสัมผัสที่ต้องการในโหมดความเหมือนร่วม K_f คือค่า Proportional เกนของการควบคุมแรงสัมผัส

ในทางกลับกันการเปลี่ยนมิติจากความเร่งเสมือน $\ddot{X}_{ref}^c$, $\ddot{X}_{ref}^d$ กลับมาเพื่อนำเข้าระบบมอเตอร์แต่ละตัว $\ddot{X}_{ref1}$, $\ddot{X}_{ref2}$ สามารถทำได้ โดยใช้ inverse matrix ของ Hadamard matrix S_2^{-1} ดังต่อไปนี้

$$\begin{bmatrix} \ddot{X}_{ref1} \\ \ddot{X}_{ref2} \end{bmatrix} = \begin{bmatrix} \frac{\beta}{(\alpha+\beta)} & \frac{\alpha}{(\alpha+\beta)} \\ \frac{1}{(\alpha+\beta)} & \frac{-1}{(\alpha+\beta)} \end{bmatrix} \begin{bmatrix} \ddot{X}_{ref}^c \\ \ddot{X}_{ref}^d \end{bmatrix} = S_2^{-1} \begin{bmatrix} \ddot{X}_{ref}^c \\ \ddot{X}_{ref}^d \end{bmatrix} \quad (22)$$

4. ผลการทดลองจากแบบจำลอง Simulation results

แบบจำลองทั้งหมดเขียนโดยโปรแกรม MATLAB Simulink หุ่นยนต์ตัวแรกถูกควบคุมโดยผู้ใช้งาน โดยที่ส่วนปลายของมอเตอร์นั้นไม่มีวัตถุใดๆมาขวางไว้ และ หุ่นยนต์ตัวที่สองจะใช้ในการสัมผัสกับวัตถุที่แข็งมาก โดยที่ค่า $\alpha = 5, \beta = 2$ นั้นหมายความว่า ค่าแรงและตำแหน่งของฝั่ง Slave robot จะถูกย่อลง 5 เท่า และ 2 เท่า ตามลำดับ การทดลองนั้นทำได้โดยการขยับหุ่นยนต์ตัวแรกเพื่อทำการเกาะกับวัตถุดังกล่าว จำนวนสี่ครั้ง ผลการทดลองของผลตอบสนองของแรงสัมผัส สามารถแสดงในรูปที่ 4(a) ผลการทดลองแสดงให้เห็นว่าตัวสังเกตการณ์ KFSO แบบใหม่ที่น่าสนใจ สามารถส่งผ่านแรงเสมือนไปยังมือของผู้ใช้งานได้ อย่างดีเยี่ยม มีผลตอบสนองที่รวดเร็ว โดยเฉพาะอย่างยิ่งในช่วงที่หุ่นยนต์สัมผัสกับวัตถุนั้น ค่าแรงที่กระทำและแรงเสมือนสะท้อนกลับมีค่าออกมาที่เท่ากันในทุกทิศทางตรงกันข้าม และมีการย่อลง 5 เท่า ผลการเปรียบเทียบระหว่างค่าตำแหน่งจาก Kalman filter และ เอนโคเดอร์สามารถแสดงได้ดังรูปที่ 4 (b) จะเห็นได้ว่าการเคลื่อนที่ของหุ่นยนต์ฝั่ง Slave นั้นมีผลตอบสนองของตำแหน่งที่เป็นอัตราส่วนย่อลง 2 เท่าเมื่อเทียบกับหุ่นยนต์ฝั่ง Master และมีทิศทางเดียวกัน จึงสามารถสรุปได้ว่าการออกแบบระบบควบคุมดังกล่าวนั้นสามารถทำได้ตามเป้าหมายที่วางเอาไว้

5. สรุป

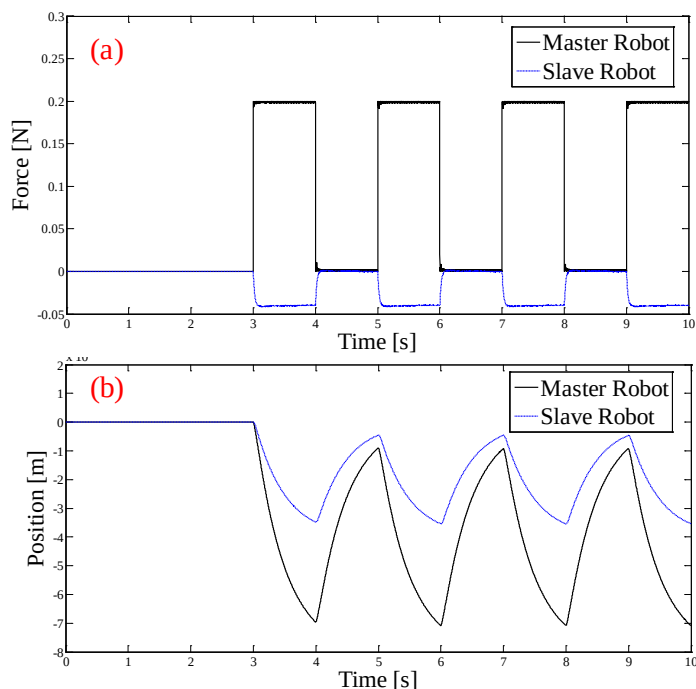
ในงานวิจัยนี้ได้นำเสนอวิธีการใหม่ ในการควบคุมแบบสองทิศทางที่สามารถกำหนดอัตราส่วนย่อ/ขยาย ทั้งผลตอบสนองของแรงและตำแหน่งได้ จากการใช้ KFSO และวิธีดังกล่าวทำให้ง่ายต่อการควบคุมทั้งแรง และตำแหน่งพร้อมกันในมิติของความเร่ง จึงทำให้ประสิทธิภาพการส่งผ่านแรงสัมผัสดีขึ้น โดยที่ไม่จำเป็นต้องใช้เซนเซอร์วัดแรงดังที่ได้แสดงไว้ในผลการทดลอง งานวิจัยดังกล่าวสามารถนำมาประยุกต์ใช้งานได้หลากหลายทั้งด้านอุตสาหกรรมและการแพทย์

6. กิตติกรรมประกาศ

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M. Eng. ในสาขา Electrical, Electronics and Information Engineering และ ปริญญาเอก D.Eng. ในสาขา Energy and Environment Science จาก Nagaoka University of Technology ประเทศญี่ปุ่นในปี 2550 และ 2553 ตามลำดับ โดยได้รับทุน Monbukagakusho จาก Ministry of Education, Culture, Sports, Science and Technology, MEXT หลังจากสำเร็จการศึกษา ได้ทำงานวิจัยหลังปริญญาเอก โดยได้รับทุนจาก Japan Society for the Promotion of Science, JSPS เป็นระยะเวลา 2 ปี ในปี 2555 เข้าทำงานในตำแหน่ง อาจารย์ ที่มหาวิทยาลัย เกษตรศาสตร์ ในสาขาวิศวกรรมไฟฟ้า งานวิจัยที่สนใจได้แก่ Rehabilitation robot, Human-robot interaction, Sensor fusion, , Tele-operated robot ได้รับรางวัลจากผลงานวิจัยได้แก่ IEEE IES student scholarship award ปี 2551 ในงาน IECON'09, Best presentation award ปี 2553 และ 2555 ในงาน TJIA'10 และ IECON'12, รางวัลผลงานวิจัยยอดเยี่ยมจากอธิการบดี Nagaoka University of Technology ในปี 2554 และ รางวัล Siew-sngiem award เพื่อวิศวกรรมไฟฟ้า ในปี 2556 รวมทั้งยังเป็นคณะกรรมการ และ ผู้อ่านบทความใน IEEE Industrial electronics society สาขา sensors and actuators อีกด้วย



การประชุมวิชาการเครือข่ายวิศวกรรมไฟฟ้า มหาวิทยาลัยเทคโนโลยีราชมงคล ครั้งที่ 6
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ขอมอบเกียรติบัตรฉบับนี้ให้เพื่อแสดงว่า

เชาวลิต มิตรสันติสุข

ผู้เขียนบทความเรื่อง

การควบคุมอัตราส่วนย่อย/ขยายแบบสองทิศทางโดยใช้ตัวสวิตกเหตุการณ์สัญญาณรบกวนจากตัวกรองคาลมานสำหรับอุปกรณ์การแพทย์

ได้รับเลือกให้เป็นบทความดีเด่น สาขาระบบควบคุมและการวัด

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