



## THESIS APPROVAL

### GRADUATE SCHOOL, KASETSART UNIVERSITY

Master of Engineering (Information and Communication Technology for Embedded Systems)

DEGREE

Information and Communication Technology for Embedded Systems

Electrical Engineering

FIELD

DEPARTMENT

TITLE: Wrist Rehabilitation Robot Using Bilateral Control for Master-Slave System

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THESIS

WRIST REHABILITATION ROBOT USING BILATERAL  
CONTROL FOR MASTER – SLAVE SYSTEM



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A Thesis Submitted in Partial Fulfillment of  
the Requirements for the Degree of  
Master of Engineering (Information and Communication Technology for Embedded Systems)  
Graduate School, Kasetsart University

2014

Saran Jarudamrongsak 2014: Wrist Rehabilitation Robot Using Bilateral Control for Master – Slave System. Master of Engineering (Information and Communication Technology for Embedded Systems), Major Field: Information and Communication Technology for Embedded Systems, Department of Electrical Engineering. Thesis Advisor: Mr. Chowarit Mitsantisuk, D.Eng. 47 pages.

Since 2007 in Thailand, the field of physical therapy has a tremendous power manful shortage, but in fact there have needed of physical therapists up to 1,446 people. It challenge research in an engineering field to build the robot as medical tools for supporting on physical therapy. The robot is applied to transfer force and movement though the robot system. Haptic technology is a tactile feedback technology which recreates the sense of touch by applying forces, vibrations, or motions to the user. This mechanical stimulation can be used to assist in the creation of virtual objects in a computer, to control such virtual objects, and to enhance the remote control of machines. Haptic devices may incorporate tactile sensors that measure forces exerted by the user on the interface. But the generally haptic technology has implemented the force sensor in device which has a limitation about bandwidth, point of measure and high cost of high resolutions sensor. In order to solve this problem, disturbance observer method is applied to estimate external force. The feedback disturbance estimation is also used to compensate an unknown disturbance from the motor side and to ensure the system's robustness. In this research, the proposed wrist robot assistive system consists of master and slave robot which has control based on bilateral control. 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. By using the proposed bilateral controller, it is possible to provide a high transparency and good perception interaction force of assisting rehabilitation training.

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Student's signature

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Thesis Advisor's signature

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## ACKNOWLEDGEMENTS

Most importantly, I would like to express my sincere gratitude to my advisor, namely Dr. Chowarit Mitsantisuk, for his consistently support of my M.Eng. study research,. Thanks for his patience, motivation, enthusiasm, and immense knowledge. Along with his guidance, the thesis had been conducted and developed with attention and right knowledgeable. It is hard to imagine of not having a good advisor and mentor for my M.Eng. study as I do have.

Besides, I appreciated for the encouragement, insightful comments, and in-depth questions of my thesis committees: Prof. Yasuharu koike and Ph.D.Pished Bunnun.

Thanks to my fellow CMIT laboratory of Kasetsart University: Phalakorn Kladjaroen, Niphun Surapong, Prawin Jingjit, Napol Varachitchai, for the stimulating discussions, the sleepless nights we were working together before deadlines, and for all the wonderful moments we had last year.

Last but not the least; I would like to thank my family: my parents Mr.Taveekiat Jarudamrongsak and Mrs.Somkid Jarudamrongsak, for giving birth to me at the first place and supporting me spiritually throughout my life.

Saran Jarudamrongsak

July, 2014

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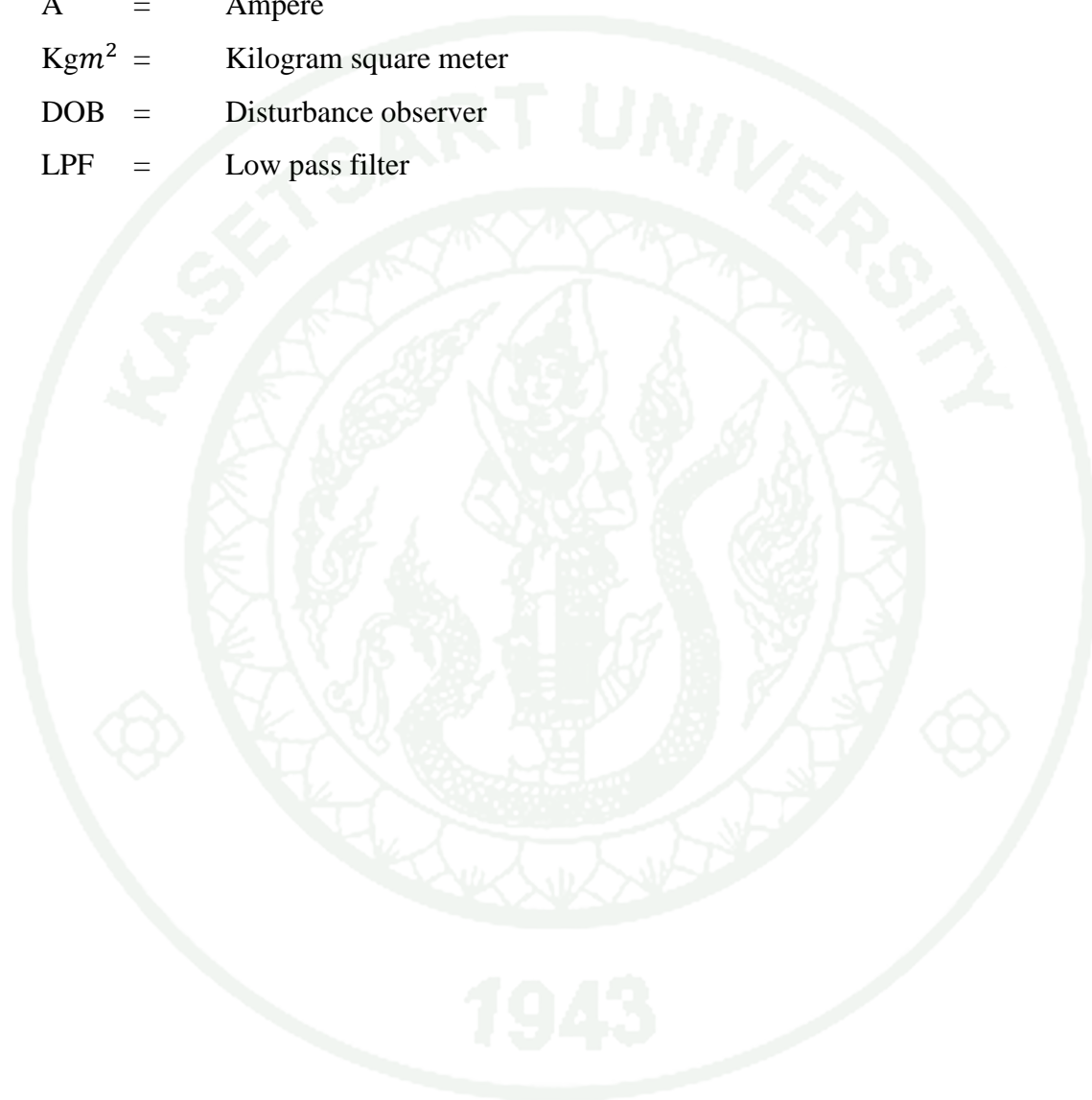
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## LIST OF ABBREVIATIONS AND SYMBOL

DOF	=	Degree of freedom
Nm	=	Newton meter
A	=	Ampere
$\text{Kgm}^2$	=	Kilogram square meter
DOB	=	Disturbance observer
LPF	=	Low pass filter



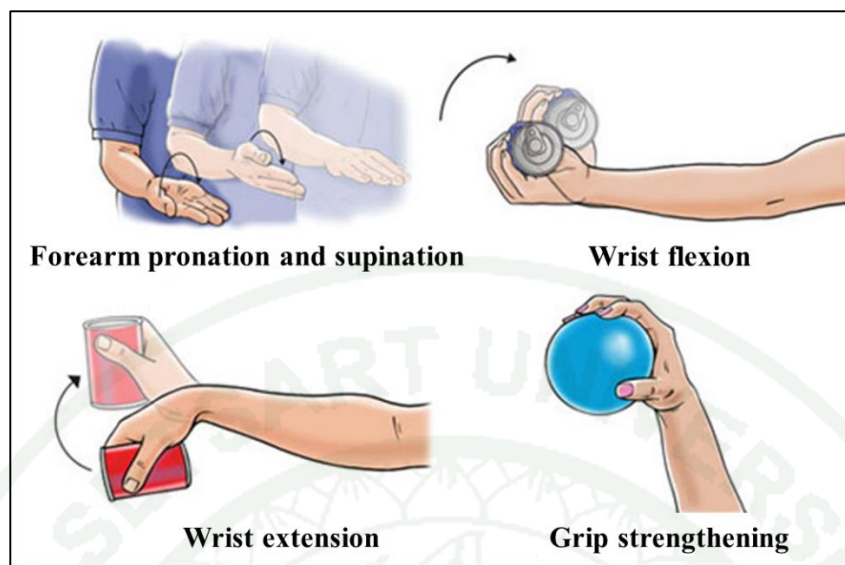
## **WRIST REHABILITATION ROBOT USING BILATERAL CONTROL FOR MASTER – SLAVE SYSTEM**

### **INTRODUCTION**

In recent years, Thailand Research Center for Health Services System conducted a research on medical workforces. The deficiency in the number of medical workforces had been found out. A slump number of doctors, nurses, and physiotherapists had been shown along the support evidence in a tremendous shortage of physical therapy field. Since 2007, 930 physiotherapists per year had been planned in purpose. However, a number of physiotherapists were required up to 215 and 1,231 people among general hospitals and community hospitals respectively. Almost 1,500 physiotherapists were urgently required at the time. Focus on additional researches, the results stated on a requirement of medical workforces supply in year 2010 till 2020 along with the change in Thailand's demographic as a major factor. This study presented a number of 2,499 and 3,700 physiotherapists for year 2010 and 2020 respectively. This significant raising in a number of physiotherapists has further highlighted an awareness of a higher medical workforce's deficiency rate. Therefore, this concentrate crisis can be enhanced through the conception of robot technology, in the form of physical therapy support tools.

There is no doubt on the challenge of using robot technology as a contribution tool towards medical therapy section. Therefore, this study was conducted under the issue of wrist rehabilitation which can be an essential solution for further physiotherapist shortage problems. The idea was come up with a design of medical robot which has ability to perform an exact waist movement between physiotherapist and patient in a different location.

Basically, the movement of a particular robot should work on the platform of wrist rehabilitation, which focuses on a range of motion exercises such as forearm pronation and supination, wrist flexion, wrist extension and grip strengthening. Each pattern of wrist rehabilitations has shown in figure 1.



**Figure 1** Basis of wrist rehabilitation pattern.

A challenge has been raised once the study of rehabilitation robot technology was conducted. A major of concern in the study is the result in creating additional alternative tool, which facilitates and reduces a distance between physiotherapist and patient. In this research, the treatment of rehabilitation can be performed with the pattern of bilateral control and force feedforward sensation through master – slave robot technology. According to several researches, haptic technology conveys the limitation of fore sensor. Such as, high cost of material, loud noise, low bandwidth, and ability to solely measure on fix position. The way to solve problems, disturbance observer method was taken into consideration in which external factors were estimated. The feedback of disturbance estimation was also used to compensate an unknown disturbance from the motor side and ensure the system's robustness.

## OBJECTIVES

An overall objectives of this thesis aims to design the robot's physical in order to apply a medical tool, as a solution in recovering the wrist rehabilitation. Through different locations, the robot will work as an intermediary between doctor and patient. The objectives of the study are discussed as follows;

1. To study the optimum method which can be solves the disadvantage of force sensor.
2. To study the robust sensorless force control method which can control the robot system.
3. To design a new mechanical system for wrist rehabilitation robot and design the test-rig experiment.
4. Applied all in the real experiment with demo version.

## LITERATURE REVIEW

In recent years, the haptic robot technology can be considered a challenge research to increase opportunities for applying on many applications. One of interesting field is a medical tools technology. Since 2007, Thailand Research Center for Health Services System conducted research on health workforce shortage about doctor, nurse, physiotherapist and etc. Therefore the haptic technology in field of rehabilitation is very interested to research. The robot by the haptic technology can be transfer movement between doctor and patient which can be solve a workforce shortage. Moreover, it will be going the new robot medical tools. This review includes 3 sections. The first section discusses the robot for wrist rehabilitation mechanical design. Section 2 covers the approaches to the design of the robot system. Section 3 about wrist rehabilitation.

Robot-assisted stroke rehabilitation has become popular as one approach to helping patients recover function post-stroke. Robotic rehabilitation requires four important elements to match the robot to the patient: realistic biomechanical robotic elements, an assistive control scheme enabled through the human–robot interface, a task oriented rehabilitation program based on the principles of plasticity, and objective assessment tools to monitor change. In this study, a seven degree-of-freedom (DOF) upper limb exoskeleton robot (UL-EXO7) is applied in a rehabilitation clinical trial for patient's stable post-stroke (Hyunchul et al., 2013). A newly–developed haptic interface for arm self–rehabilitation based on bilateral control. In order to acquire enough motion range for the rehabilitation, the X–Y tables with two degrees–of–freedom are utilized as the haptic system. This integration can provide the self-rehabilitation suitable for the patients with hemiplegia (Morito et al., 2013). Then, robotic devices for the upper extremity have primarily focused on the proximal joints, with only a few devices designed specifically for forearm and wrist rehabilitation, which is critical for the restoration of independence in activities of daily living. They present the kinematic design of a serial mechanism, the RiceWrist-S, for forearm and wrist rehabilitation, and compare its range of motion and torque output capabilities to a previously reported parallel mechanism and to requirements developed from assessment of daily activities. The RiceWrist-S design meets or exceeds targets for range of motion and torque in all

degrees of freedom (Pehlivan et al., 2012). Moreover, this thesis focus on wrist rehabilitation robot design. In 1991, a novel robot, MIT-MANUS, was introduced to study the potential that robots might assist in and quantify the neuro-rehabilitation of motor function. MIT-MANUS proved an excellent tool for shoulder and elbow rehabilitation in stroke patients, showing in clinical trials a reduction of impairment in movement's confined to the exercised joints. (Charles et al., 2005; Krebs et al., 2007) MIT-MANUS designed to provide three rotational degrees-of-freedom. Another one, the Wrist Gimbal, a three degree-of-freedom (DOF) exoskeleton developed for forearm and wrist rehabilitation. Wrist Gimbal has three active DOF, corresponding to pronation/supination, flexion/extension and adduction/abduction joints. Rubber hard stops for each axis, an emergency stop button and software measures ensured safe operation. They present the specifications of Wrist Gimbal in comparison with similar devices in the literature and example data collected from a healthy subject (Martinez et al., 2013). Understanding the dynamics of wrist rotation s is important for many fields, including biomechanics, rehabilitation and motor neuro science. This research provides an experiment ally based mathematical model of wrist rotation dynamics in Flexion–Extension (FE) and Radial Ulna Deviation (RUD), and characterizes the torques required to overcome the passive mechanical impedance of wrist rotations. We found that the wrist's passive stiffness is the major impedance the neuromuscular system must overcome to rotate the wrist. Inertia and passive damping only become important for very fast movements (Charles and Hogan, 2011). As a stage toward a complete upper-arm motion assisted exoskeleton robot (7DOF) this research focused on the development of a 2DOF exoskeleton robot to rehabilitate and to ease wrist joint movements. The proposed 2DOF ExoRob is designed to be worn on the lateral side of the forearm in order to provide naturalistic movements (flexion/extension and radial/ulnar deviation) of the wrist joint. A kinematic model of ExoRob has been developed based on modified Denavit-Hartenberg notations (Rahman et al., 2010). Last but not least, the Robot design is the rehabilitation robot which detects and analyzes the intention that man tries to move a wrist with biological signal, such as muscle potential, and makes a wrist exercise as one's intention. It consists of a grip for wrists, an actuator, a biological signal primary means, biological signal processing part, and a rehabilitation controller (Yamamoto et al., 2012). Lastly, a robot called the Closed-chain Robot for

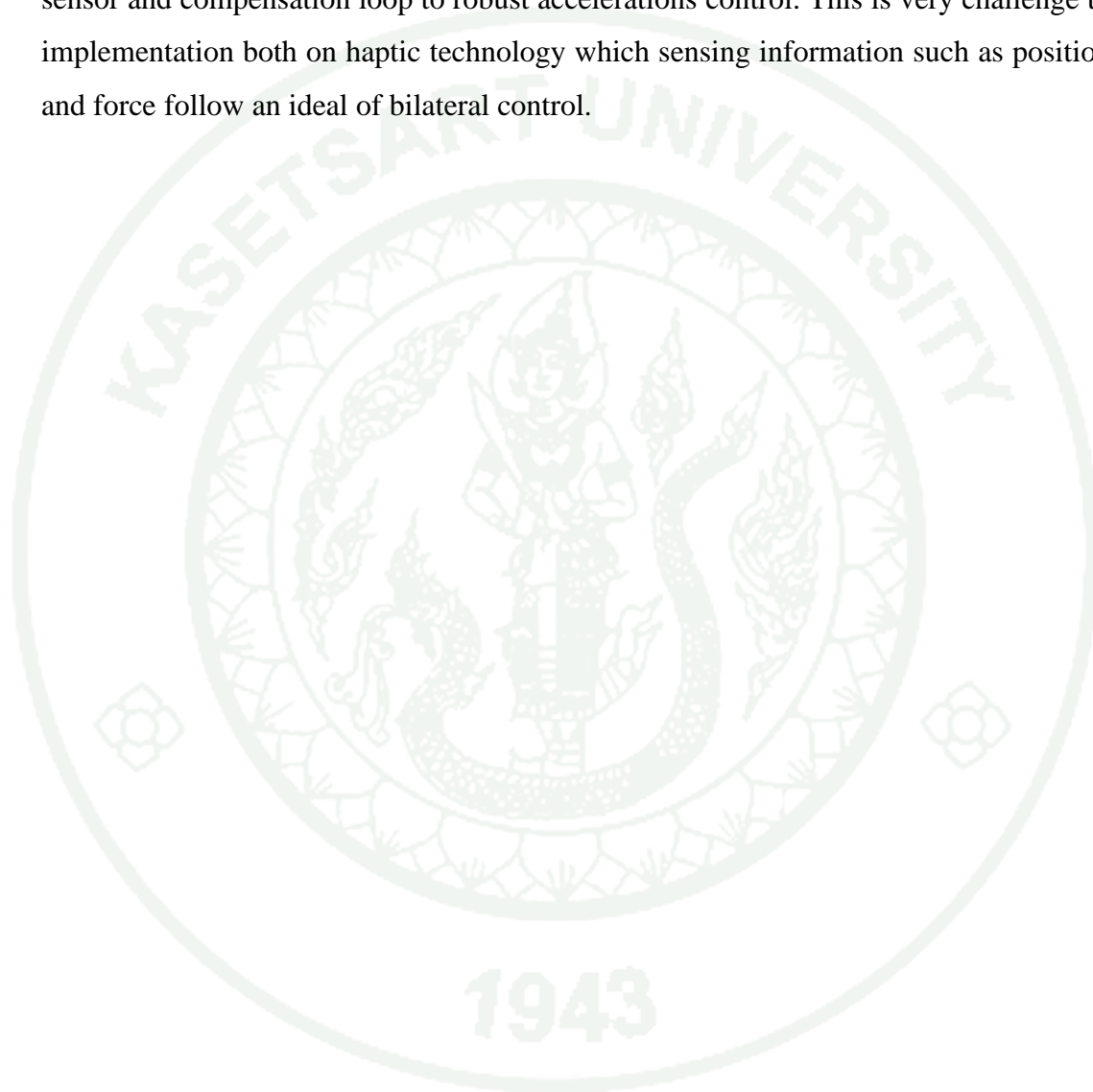
Assisting in Manual Exercise and Rehabilitation (CRAMER) was developed to assist impaired persons in making three degree-of-freedom movements of the forearm and wrist with a parts and machining cost of less than \$1500. CRAMER is intended to engage patients in their rehabilitation therapy by having them play computer-based exercise games. The remote for Nintendo's Wii was integrated into the handle of the robot in an attempt to allow patients to play the high-quality yet affordable motion-based games that have been developed for the Wii (Spencer et al., 2008).

Recent machines are hoped to have a haptic ability to work in open environment. Haptic motion control is based on position control and force control. To realize the position control and especially force control, the attainment of robustness is essential. This research selects a disturbance observer to attain the robust acceleration control. They analyze a disturbance observer with the focus on parameter variations and shows that the cut-off frequency depends on parameter variations. The design method of observer gains is also proposed (Kobayashi et al., 2005, 2007). Moreover, the master-slave robot system has controlled by bilateral control. Four-channel controller which is hybrid of position and force in the acceleration dimension based on disturbance observer can be divided into two modes: common and differential modes. Position is controlled in differential mode space, force is controlled in common mode space. According to this method, design of bilateral control can be treated as position control and force control about one robot separately. An analysis and design of bilateral control based on disturbance observer are discussed (Matsumoto, 2003). The novel of bilateral control method is introduced to realize multiple input or plural output bilateral system. In the proposed multilateral control, interactivity and synchronism are achieved easier than conventional control. It shows the system has wide range of application. 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 (Suzuyama et al., 2006). The newest, as haptic technology has advanced in the past decade, many sensor devices have been built and commercialized for providing the sense of action/reaction forces. This presents formulation and application of a Kalman filtering technique for control of master-slave robots contacting environment in a bilateral control. A Kalman-filter-based state

observer and a Kalman-filter-based disturbance observer have been designed to estimate action/reaction forces (Mitsantisuk et al., 2012).

Successful motor rehabilitation of stroke, TBI and SCI subjects requires an intensive and task-specific therapy approach. The article presents clinically viable devices for the upper and lower extremity rehabilitation, which have been developed by our group. The Bi-Manu-Track, enables the bilateral practice of a forearm and wrist movement, and is currently tested. For gait rehabilitation after stroke, the electromechanical gait trainer GT I has proven effective as compared to treadmill training with Body weight support (BWS). A first open study included 12 severely affected chronic subjects (> 6 months post) who suffered from at least moderate wrist and finger spasticity and could merely move the shoulder and el-bow joints. Three weeks of daily therapy `a 30 min resulted in a muscle tone reduction for 1 to 2 scores on the Modified Ashworth score (0-5), proximal muscle functions improved in five out of the 12 subjects without a carry-over effect in daily practice. The latter has been positively evaluated in re-cent meta-analysis. So far, 38 subjects have been included (55 are planned), the preliminary results show a clearly better improvement in the experimental group for the primary outcome variable, the Fugl-Meyer Motor Score (Schmidt et al., 2004). Moreover, to investigate the immediate effects of bilateral upper-extremity sanding exercises on conduction and morphologic characteristics of the median and ulnar nerves at the wrist in hemiparetic subjects and control subjects. The article present a method by bilateral nerve conduction tests and ultrasonography evaluations were performed on each subject before and immediately after a 30-minute bilateral sanding exercise with a frequency of 5 repetitions per minute. The effects of exercises on bilateral median and ulnar wrist nerves were assessed with the use of sensory and motor nerve conduction velocity tests and by width/thickness ratios in ultrasonographic evaluations. The median and ulnar nerves at the wrist in hemiparetic subjects before sanding exercises showed different conduction characteristics compared with control subjects. Their affected side also demonstrated significant conduction and morphologic changes after the exercises (Huang et al., 2011).

Wrist rehabilitation robot has designed since year 1991 for an optimum mechanical of the robot such as MIT-MANUS (3DOF), Wrist Gimbal (3DOF) and ExoRob (2DOF) which has an error control with force sensor or load cell. Then the feature about disturbance observer can estimation an external force by without force sensor and compensation loop to robust accelerations control. This is very challenge to implementation both on haptic technology which sensing information such as position and force follow an ideal of bilateral control.



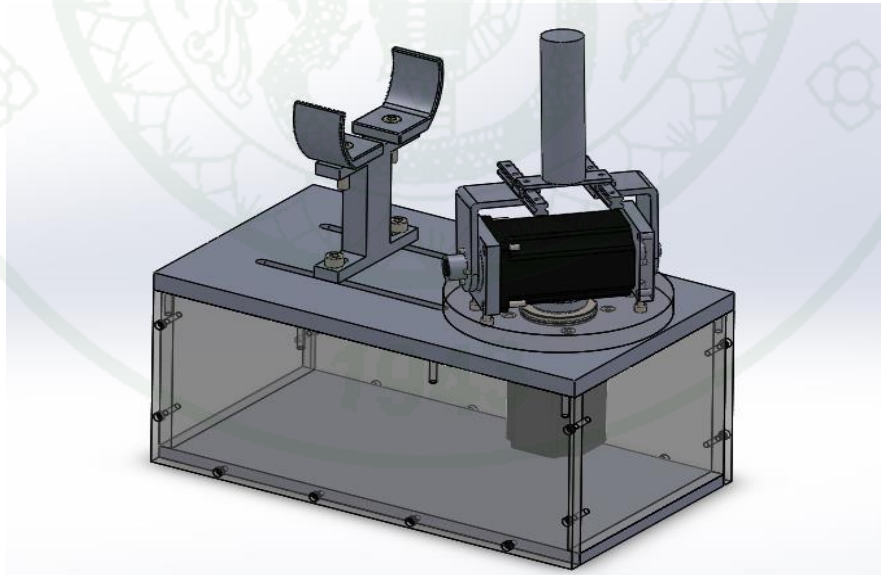
## MATERIAL AND METHODS

### Material

This chapter stated on the design of robot system, continued with the study of materials used during the research, and ultimately focuses on the method of investigation and implementation of proposed approach.

### Design

The major part of the design of robot system consists of two joint per side of the system, which supports for each of flexion/extension (FE) and radial deviation/ulnar deviation (RUD). The system is divided into two sides. One side is used by physiotherapists. And other side is used by the patient. Both sides are composed of the same structure of the robot model. In this thesis, the robot system has designed by solidworks 3D programming, as shown in Figure 2.



**Figure 2** Model of robot rehabilitation for wrist.

1. AC servo motor and amplified.

1.1. Yaskawa.

a. SGDM 02ADA 400 watt, SGMAH 02AAA41 (2 set).

b. SGDM 02ADA 400 watt, SGMAH 02AAA21 (2 set).

**Table 1** Parameter of servo motor

Serial NO.	Item	Value	Unit
<b>SGMAH-02AAA21</b> (Straight without key)	Rate torque	0.64	[Nm]
	Rate current	2.1	[A]
	Inertia moment	0.106	$[\times 10^{-4} \text{kgm}^2]$
	Torque constant	0.327	[ Nm/A]
<b>SGMAH-02AAA41</b> (Straight with key)	Rate torque	0.64	[Nm]
	Rate current	2.1	[A]
	Inertia moment	0.106	$[\times 10^{-4} \text{kgm}^2]$
	Torque constant	0.327	[ Nm/A]

2. Computer and interface card.

2.1. Computer: Pentium4, ram 1GB, hard disk 80 GB, RT-Linux operating system. Digital multi-meter.

2.2. Interface card.

a. PCI-6205C: Encoder pulses counter board.

b. PCI-3341A: Digital to analog output board.

3. Software

3.1. RT-Linux with REDHAT 9.0

4. Mechanic aluminum parts.

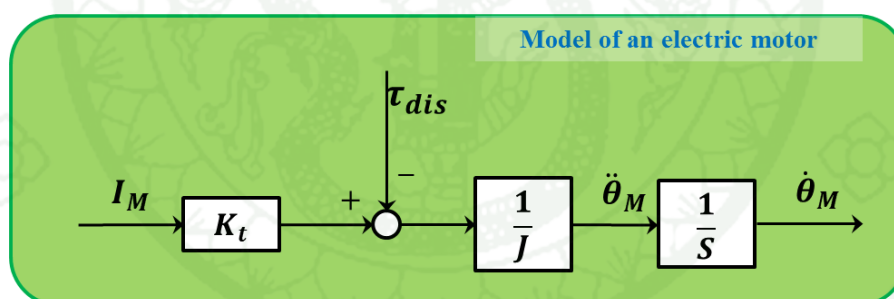


**Figure 3** Aluminum material

5. Circuit accessories.

### Method

#### Acceleration control by Disturbance Observer



**Figure 4** Structure of electrical motor.

A disturbance observer (DOB), which was proposed by Kouhei Ohishi, is a good candidate for attainment of robust acceleration control. Disturbance observers can identify the total mechanical load torque and parameter changes. A control system based on disturbance observer is an effective method to estimate disturbance force  $\tau_{dis}$  of  $\tau_l$ , which is used to compensate the disturbance torque on the motor side and to assure the robustness of the system in acceleration dimension. The model of an electric motor is controlled under the ideal of current source, a model of the joint is represented in Figure 4.

Where:  $\tau_{dis}$  external force;  
 $I_M$  motor current;  
 $\ddot{\theta}_M$  acceleration of motor  
 $J$  Moment inertia of the actuator;  
 $K_t$  Torque coefficient of the actuator.

This subsection introduces acceleration controller by a disturbance observer. It can be used to generate force by dynamic equation of an electrical motor that represented by multiply motor current  $I_M$  as shown in an equation.

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

Where  $n$  denotes the nominal value at the parameter

The inertia  $J$  will change according to the mechanical configuration of motion system.

$$J = J_n + \Delta J \quad (2)$$

The torque coefficient will vary according to the rotor position of electric motor due to irregular distribution of magnetic flux on the surface of rotor.

$$K_t = K_{tn} + \Delta K_t \quad (3)$$

The design structure of the disturbance observer is shown in Figure 5. The disturbance torque is estimated from the input motor current  $I_M$  and acceleration response  $\ddot{\theta}_M$  as follows,

$$J_n \ddot{\theta}_M = I_M K_{tn} - \tau_{dis} \quad (4)$$

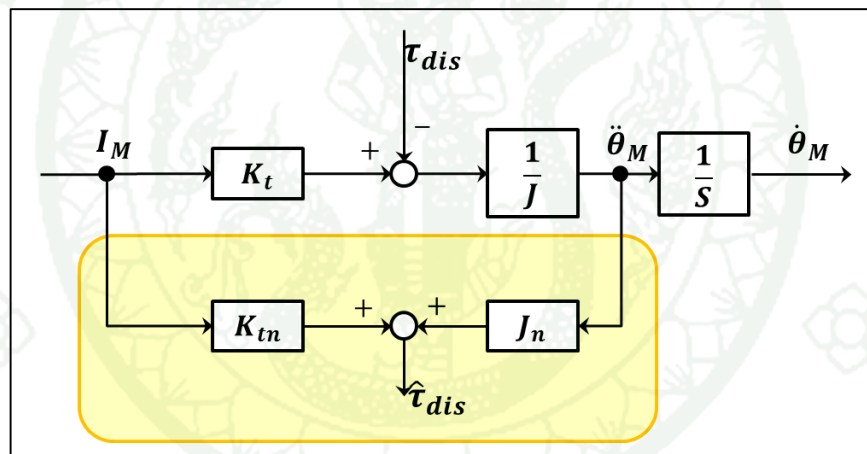
Where:  $J_n$  nominal inertia.  
 $K_{tn}$  nominal torque coefficient.

Here, the disturbance torque  $\tau_{dis}$  is represented as follows:

$$\tau_{dis} = (J - J_n)\ddot{\theta}_M + (K_{tn} - K_t)I_M + \tau_f + D\dot{\theta}_M + \tau_{ext} \quad (5)$$

In the equation(5), the first term is the torque pulsations due to the inertia variation. The second term is the torque pulsations due to the variation of torque coefficient. The third and fourth terms denote the Coulomb and the viscous friction, respectively. The last term is the reaction torque caused by external torque. Equation (4) can be transformed into

$$\tau_{dis} = I_M K_{tn} - J_n \ddot{\theta}_M \quad (6)$$



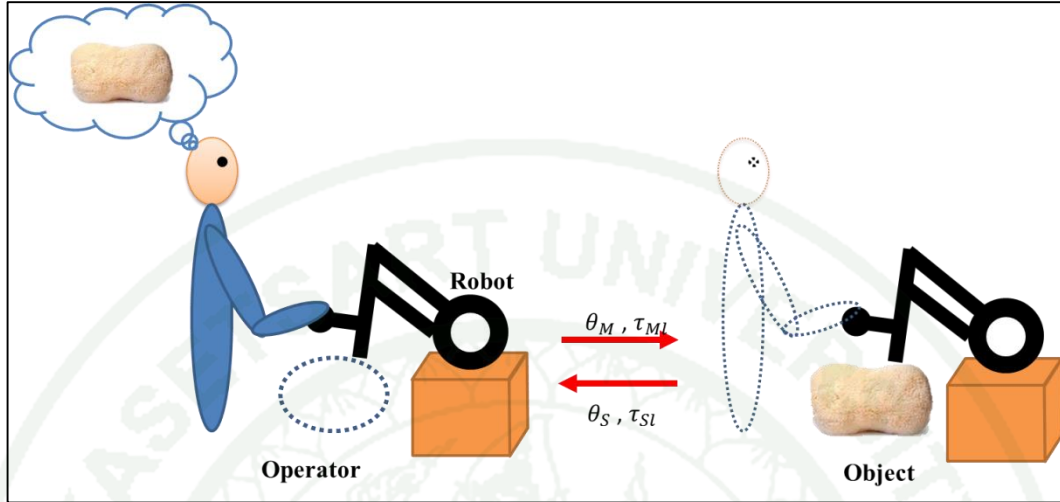
**Figure 5** Ideal of disturbance observer.

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. The estimated disturbance torque is obtained from the velocity response  $\dot{\theta}_M$  and the current  $I_M$  of the motor, as shown in Figure 5. Equation (7) shows that the disturbance torque is estimated through the first-order low-pass filter

$$\hat{\tau}_{dis} = \frac{G_{dis}}{S + G_{dis}} (I_M K_t - J_n \ddot{\theta}_M) \quad (7)$$



## Bilateral Control



**Figure 7** Image of bilateral control.

In the bilateral control system, information matching of force and position base on Newton's law of action-reaction, is necessary to reproduce of the interaction force of rehabilitation training as shown in Figure 7. The position of the master and the slave are defined as  $\theta_M$  and  $\theta_S$ . The operational force and reaction force from the environment are defined as  $\tau_{Ml}$ , and  $\tau_{Sl}$ . The target of the bilateral control is the difference between the positions of master  $\theta_M$  and the position of slave  $\theta_S$  given by equation (10).

$$\theta_M - \theta_S = 0 \quad (10)$$

Moreover, follow the action-reaction law indicates sum of force between master and slave which should be zero, as  $\tau_{Ml}$  and  $\tau_{Sl}$  respectively, given by equation (11).

$$\tau_{Ml} + \tau_{Sl} = 0 \quad (11)$$

However, the ideal of bilateral control requires which equation (10) and (11) at the same time. And in this study, equation (18) and equation (19) are integrated in the acceleration dimension.

$$\ddot{\theta}_{Mref} + \ddot{\theta}_{Sref} = 0 \quad (12)$$

$$\ddot{\theta}_{Mref} - \ddot{\theta}_{Sref} \rightarrow 0 \quad (13)$$

It can be described on two control mode, namely, common mode, as shown in equation (20), and differential mode, as shown in the equation (21). Each mode is controlled separately in the acceleration dimension. In order to obtain information for the modal space design, the force estimations at the master side  $\hat{\tau}_{Mdis}$  and the slave side  $\hat{\tau}_{Sdis}$  are transformed into the virtual forces in the common mode,  $\hat{\tau}_{ext}^c$ , and the differential mode,  $\hat{\tau}_{ext}^d$ , by using the Hadamard matrix  $H_2$ . On other side, the position signals from the encoder at the master side,  $\theta_M$ , and the slave side,  $\theta_S$ , are transformed into the virtual positions in the common mode,  $\hat{\theta}_{ext}^c$ , and the differential mode,  $\hat{\theta}_{ext}^d$ , by using  $H_2$ .

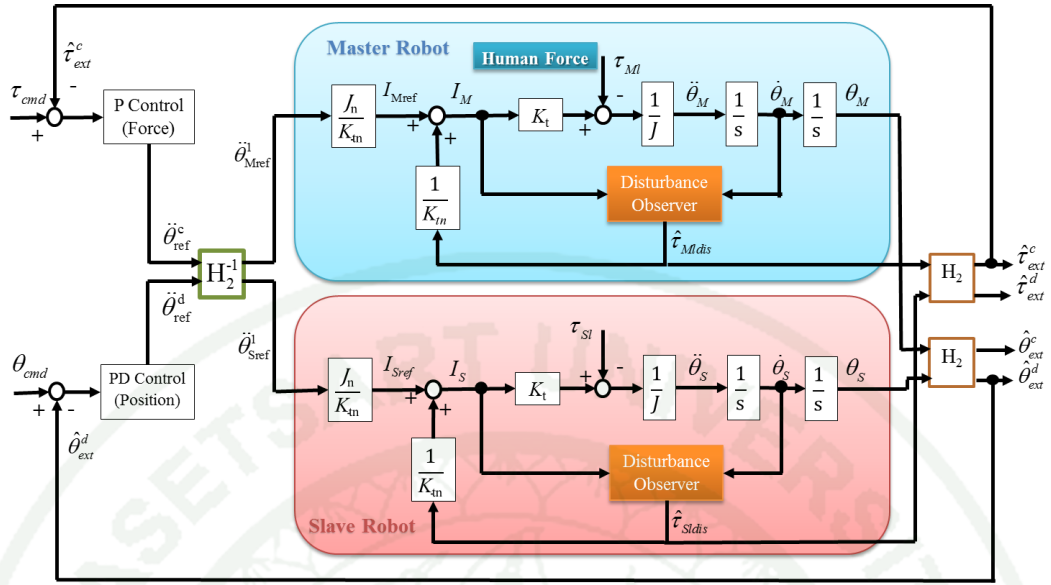
$$\begin{bmatrix} \hat{\tau}_{ext}^c \\ \hat{\tau}_{ext}^d \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \hat{\tau}_{Mdis} \\ \hat{\tau}_{Sdis} \end{bmatrix} = H_2 \begin{bmatrix} \hat{\tau}_{Mdis} \\ \hat{\tau}_{Sdis} \end{bmatrix} \quad (14)$$

$$\begin{bmatrix} \hat{\theta}_{ext}^c \\ \hat{\theta}_{ext}^d \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \theta_M \\ \theta_S \end{bmatrix} = H_2 \begin{bmatrix} \theta_M \\ \theta_S \end{bmatrix} \quad (15)$$

The modal space designed for each mode is controlled in acceleration dimension as show in equation (22) and (23).

$$\ddot{\theta}_{ref}^c = (\tau_{cmd}^c - \hat{\tau}_{ext}^c) P_f \quad (16)$$

$$\ddot{\theta}_{ref}^d = (\theta_{cmd}^d - \hat{\theta}_{ext}^d) (P_p + D_p) \quad (17)$$



**Figure 8** Block diagram of the propose bilateral control.

where  $\tau_{cmd}^c$  is the force command,  $\theta_{cmd}^d$  is the position command,  $P_f$  is the proportional gain of force control and  $P_p, D_p$  are proportional gain and derivative gain of the position control respectively, as shown in Figure 11.

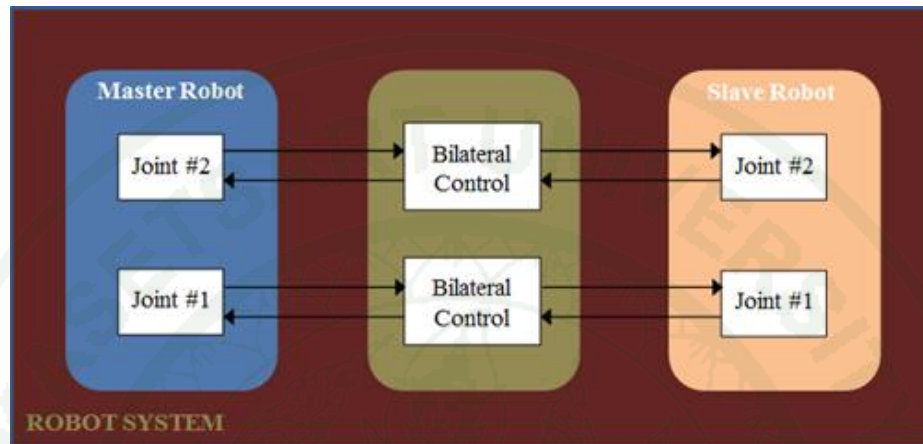
While the equation (22) shows the controller of the common mode which is a force servo control, equation (23) is the differential mode which is a position regulator. In order to transform of acceleration control signal from modal space to real space, the invest Hadamard matrix  $H_2^{-1}$  is applied. Which is calculated as follows,

$$\begin{bmatrix} \ddot{\theta}_{Mref} \\ \ddot{\theta}_{Sref} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \ddot{\theta}_{ref}^c \\ \ddot{\theta}_{ref}^d \end{bmatrix} = H_2^{-1} \begin{bmatrix} \ddot{\theta}_{ref}^c \\ \ddot{\theta}_{ref}^d \end{bmatrix} \quad (18)$$

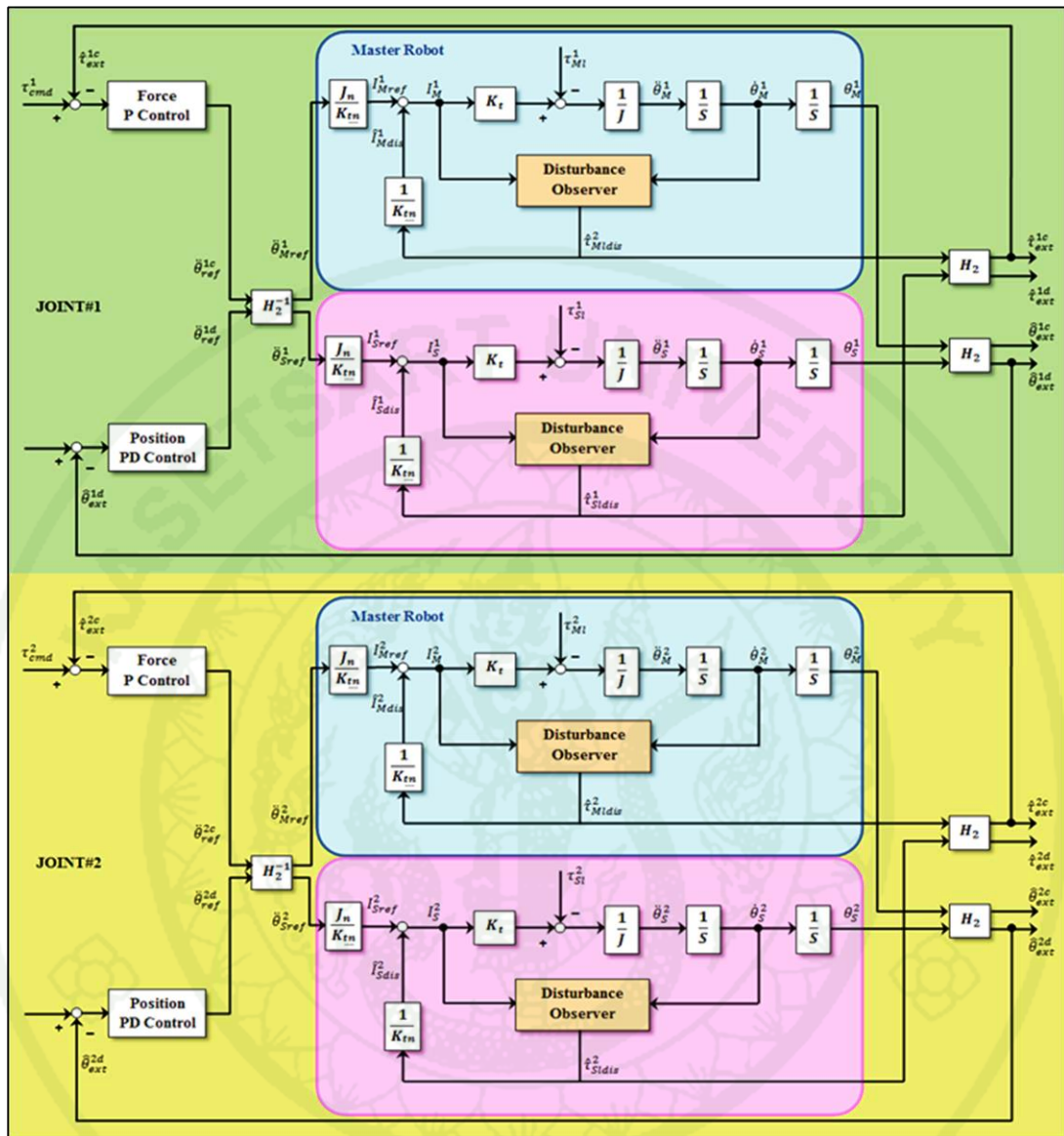
Where  $\hat{\theta}_{ref}^c$  and  $\hat{\theta}_{ref}^d$  are acceleration control signals in the common and differential modes, respectively.  $\ddot{\theta}_{Mref}$  and  $\ddot{\theta}_{Sref}$  are acceleration control signals at master and slave side.

Figure 13 shows a design of bilateral control system by using the disturbance observer in this thesis as shown in equations (10) – (24). Figure 12 shows an overview

of rehabilitation robot system. It can be designed by using two bilateral control loops for two joints of the robot, joint#1 and joint#2 are denote by superscript number 1 and 2 as shown in Figure13.



**Figure 9** Block diagram of robot system overview.



**Figure 10** Block diagram of the robot system.

### Experimental Setup

This section will focus on the wiring circuit of the servo motor which it consists of amplified circuit, input command and output response.

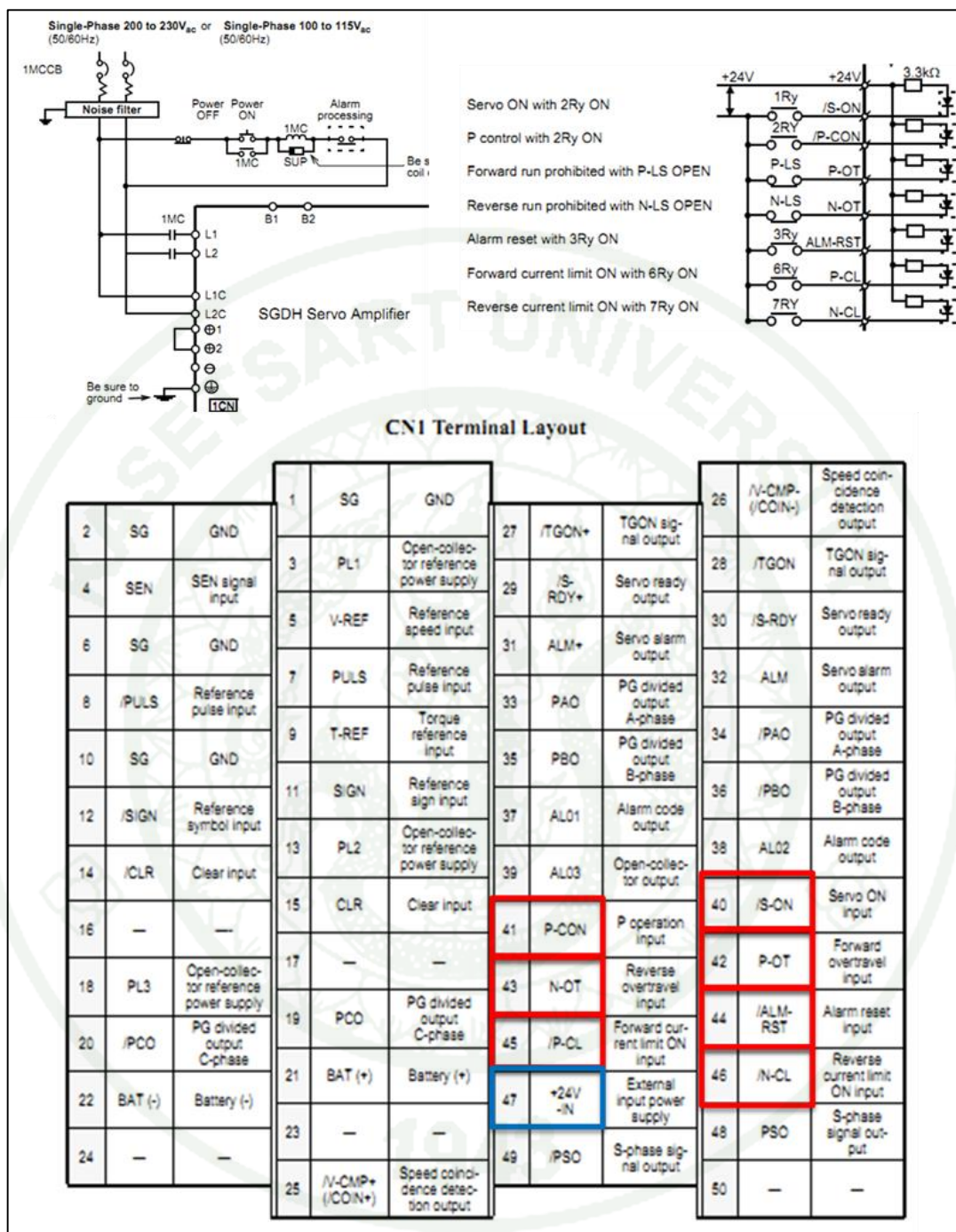


Figure 11 Servo amplified circuit.

Figure 14 shows the servo amplified wiring circuit to standby a servo motor. It consist of two part are main circuit and servo setting circuit. Main circuit, L1 and L2, is 220 volt AC. another, setting circuit is represent by Pin 40-46 wiring on GND and Pin 47 wiring on 24 volt DC.

Moreover, input command can be varied between -10 and 10 volt DC. In order to adjust the rate torque between -300 % to 300 % as shown in Figure 15.

**CNI Terminal Layout**

2	SG	GND	1	SG	GND	27	/TGON+	TGON signal output	26	/V-CMP- (/COIN-)	Speed coincidence detection output
4	SEN	SEN signal input	3	PL1	Open-collector reference power supply	29	/S-RDY+	Servo ready output	28	/TGON	TGON signal output
6	SG	GND	5	V-REF	Reference speed input	31	ALM+	Servo alarm output	30	/S-RDY	Servo ready output
8	/PULS	Reference pulse input	7	PULS	Reference pulse input	33	PAO	PG divided output A-phase	32	ALM	Servo alarm output
10	SG	GND	9	T-REF	Torque reference input	35	PBO	PG divided output B-phase	34	/PAO	PG divided output A-phase
12	/SIGN	Reference symbol input	11	SIGN	Reference sign input	37	AL01	Alarm code output	36	/PBO	PG divided output B-phase
14	/CLR	Clear input	13	PL2	Open-collector reference power supply	39	AL03	Open-collector output	38	AL02	Alarm code output
16	—	—	15	CLR	Clear input	41	P-CON	P operation input	40	/S-ON	Servo ON input
18	PL3	Open-collector reference power supply	17	—	—	43	N-OT	Reverse overtravel input	42	P-OT	Forward overtravel input
20	/PCO	PG divided output C-phase	19	PCO	PG divided output C-phase	45	/P-CL	Forward current limit ON input	44	/ALM-RST	Alarm reset input
22	BAT (-)	Battery (-)	21	BAT (+)	Battery (+)	47	+24V -IN	External input power supply	46	/N-CL	Reverse current limit ON input
24	—	—	23	—	—	49	/PSO	S-phase signal output	48	PSO	S-phase signal output
			25	/V-CMP+ (/COIN+)	Speed coincidence detection output				50	—	—

**Figure 12** Torque command input connection.

The output response is encoder signals of servo motor which is consisted of A phase, B phase and Z phase, as shown in Pin 33-34, Pin 35-36 and Pin 19-20 respectively of Figure 16.

CNI Terminal Layout											
2	SG	GND	1	SG	GND	27	/TGON+	TGON signal output	26	/V-CMP- (/COIN-)	Speed coincidence detection output
4	SEN	SEN signal input	3	PL1	Open-collector reference power supply	29	/S-RDY+	Servo ready output	28	/TGON	TGON signal output
6	SG	GND	5	V-REF	Reference speed input	31	ALM+	Servo alarm output	30	/S-RDY	Servo ready output
8	/PULS	Reference pulse input	7	PULS	Reference pulse input	33	PAO	PG divided output A-phase	32	ALM	Servo alarm output
10	SG	GND	9	T-REF	Torque reference input	35	PBO	PG divided output B-phase	34	/PAO	PG divided output A-phase
12	/SIGN	Reference symbol input	11	SIGN	Reference sign input	37	AL01	Alarm code output	36	/PBO	PG divided output B-phase
14	/CLR	Clear input	13	PL2	Open-collector reference power supply	39	AL03	Open-collector output	38	AL02	Alarm code output
16	—	—	15	CLR	Clear input	41	P-CON	P operation input	40	/S-ON	Servo ON input
18	PL3	Open-collector reference power supply	17	—	—	43	N-OT	Reverse overtravel input	42	P-OT	Forward overtravel input
20	/PCO	PG divided output C-phase	19	PCO	PG divided output C-phase	45	/P-CL	Forward current limit ON input	44	/ALM-RST	Alarm reset input
22	BAT (-)	Battery (-)	21	BAT (+)	Battery (+)	47	+24V -IN	External input power supply	46	/N-CL	Reverse current limit ON input
24	—	—	23	—	—	49	/PSO	S-phase signal output	48	PSO	S-phase signal output
			25	/V-CMP+ (/COIN+)	Speed coincidence detection output				50	—	—

Figure 13 Encoder output connection.

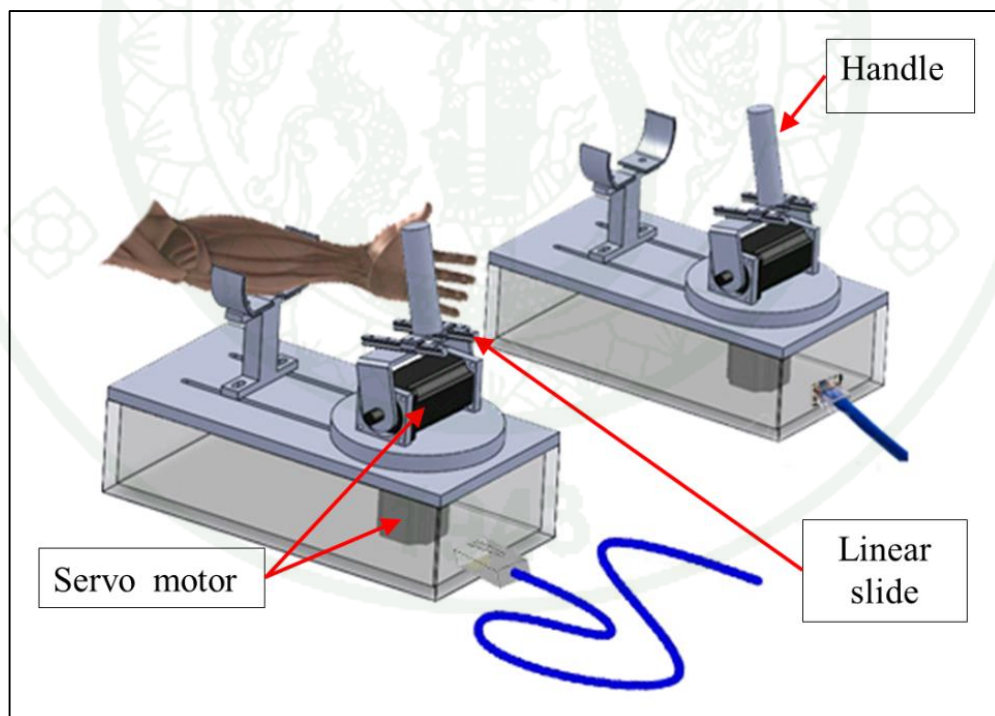
## RESULTS AND DISCUSSION

This chapter starts on the simulation result through MATLAB programming. Likewise, the results of experiment related to the prototype version of robot will be discussed.

### Results

#### 1. Simulation

First, this chapter introduces about the robot operation. Refers to Figure 13, the wrist rehabilitation robot system is worked on bilateral control, which gave the command input  $\tau_{cmd}^c$  and  $\theta_{cmd}^d$  are zero. Then, it means the robot has moved follow as the disturbance force or external force only. In this simulation, the disturbance force of wrist rehabilitation robot system is a wrist movement by the user.



**Figure 14** Wrist rehabilitation robot system operation.

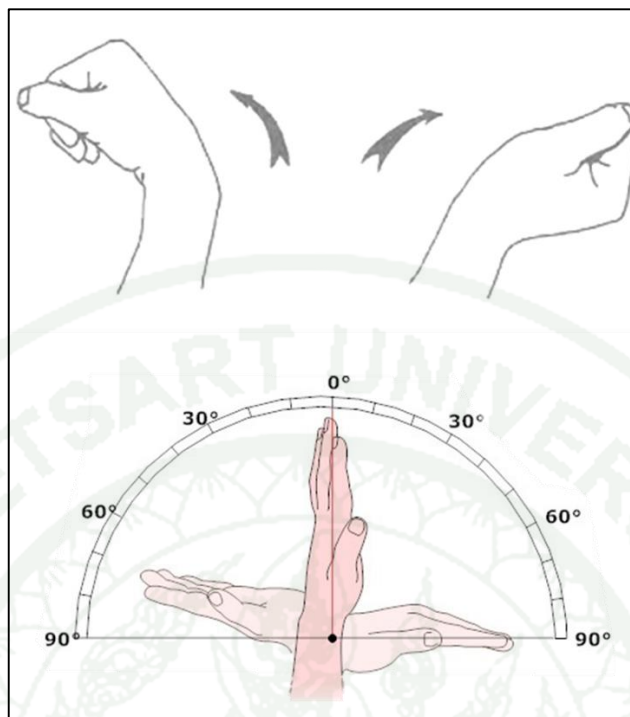
The results from MATLAB simulation with a model of wrist rehabilitation robot are shown in 5 parts of system responses. It consists of force estimation by disturbance observer, position error comparison between with and without disturbance compensation loop, position response, force response and error response of bilateral control. The main features of study are disturbance observer method and bilateral control for wrist rehabilitation robot.

**Table 2** Parameter used

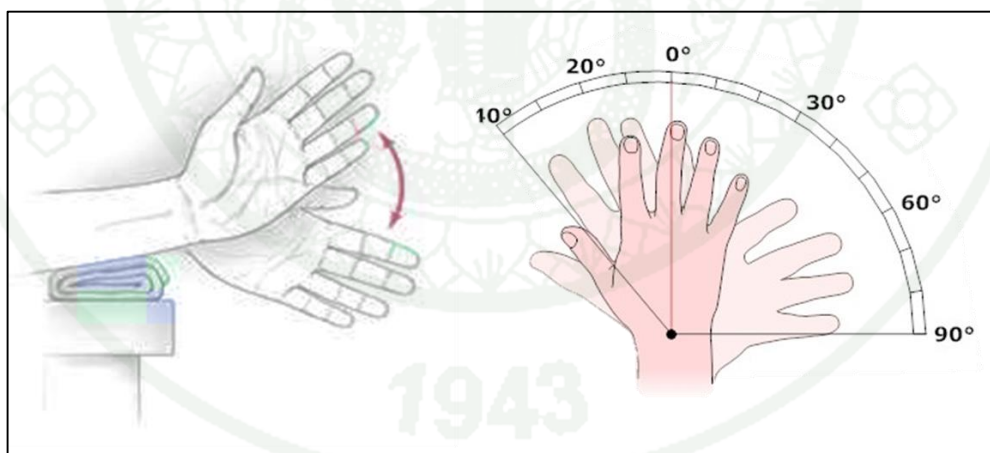
Controller parameters	Symbol	Value	Unit
Inertia moment	$J_n$	0.106	$10^{-4} \times Kg m^2$
Torque constant	$K_{tn}$	0.327	$Nm/A$
Cutoff frequency of low-pass-filter	$G_{dis}$	1000	$rad/s$
P gain of force control loop	$P_f$	4.3	
P gain of position control loop	$P_p$	1500	
D gain of position control loop	$D_p$	1600	

### 1.1 supposing input

The operation of the robot system is supported on two DOF or two joint movements. The first joint is moves on flexion and extension dimension of human wrist that has limitation on -90 to 90 degree, as shown in Figure 18. The second joint is moves on radial deviation and ulnar deviation of human wrist that has limitation on -20 to 90 degree, represent in Figure 19.

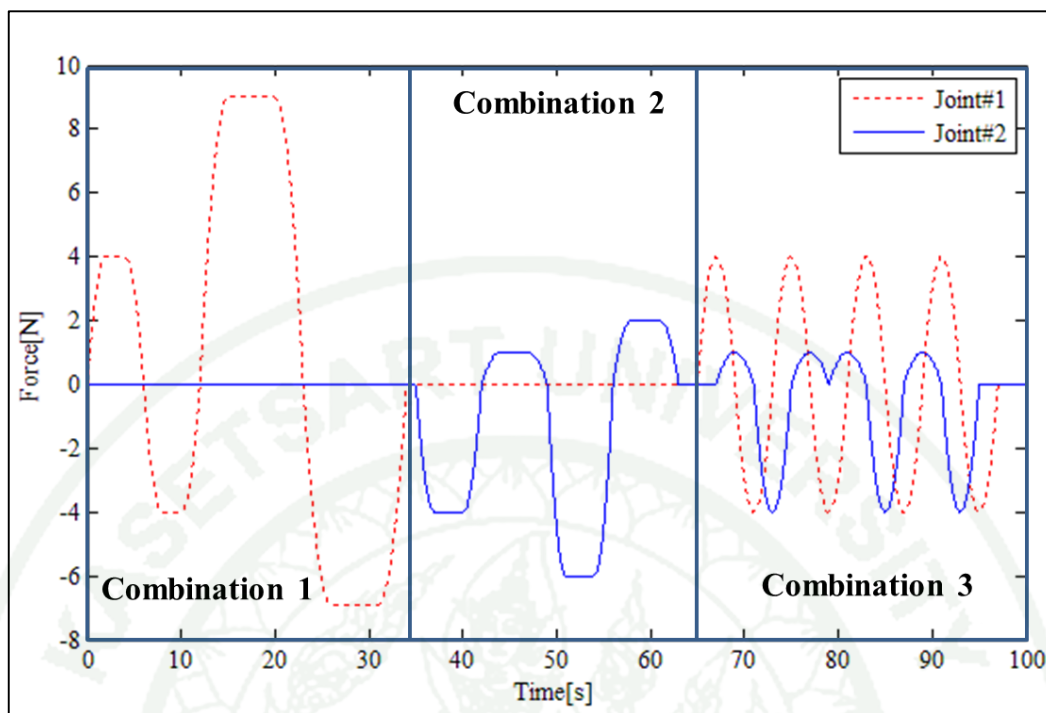


**Figure 15** flexion and extension dimension of human wrist.



**Figure 16** deviation and ulnar dimension of human wrist.

Figure 20 shows the external disturbance force input. It is generated by function generator in Matlab programming. The signal of generation is basis movement of human wrist and signaling into a disturbance force of the robot system.

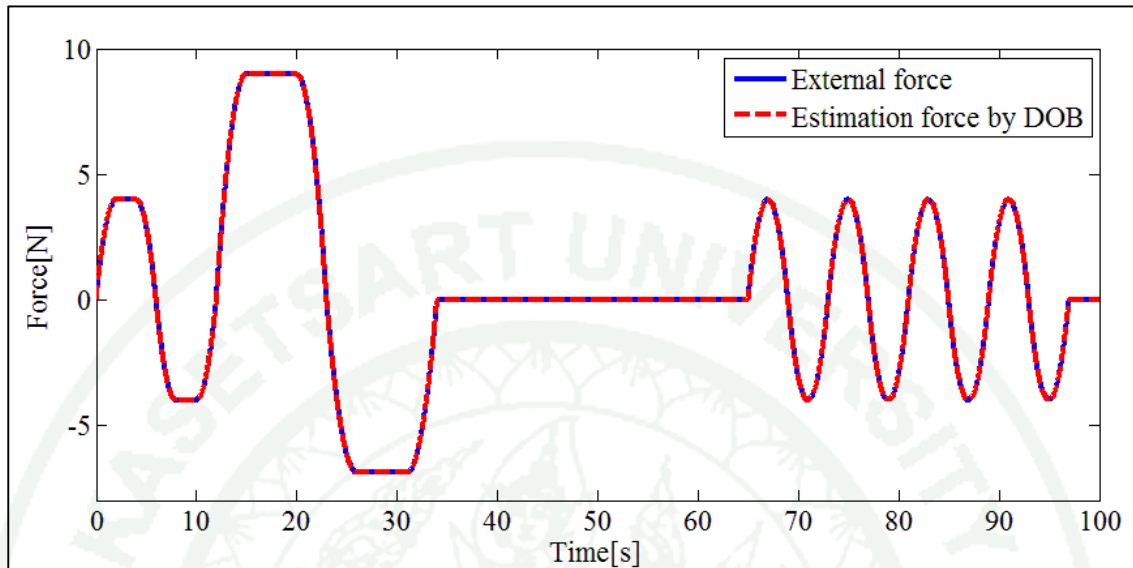


**Figure 17** Force supposing input

Simulation input signal has imagined in three phases combination movement. Firstly, the robot is operated on the first joint only which can be move left and right. Secondly, the robot is operated on second joint, it can be move up and down. Lastly, the robot actives with both joint, it can be move around of human wrist like a circle movement. External force can be assumed to be human force by multiply constant gain with position and velocity.

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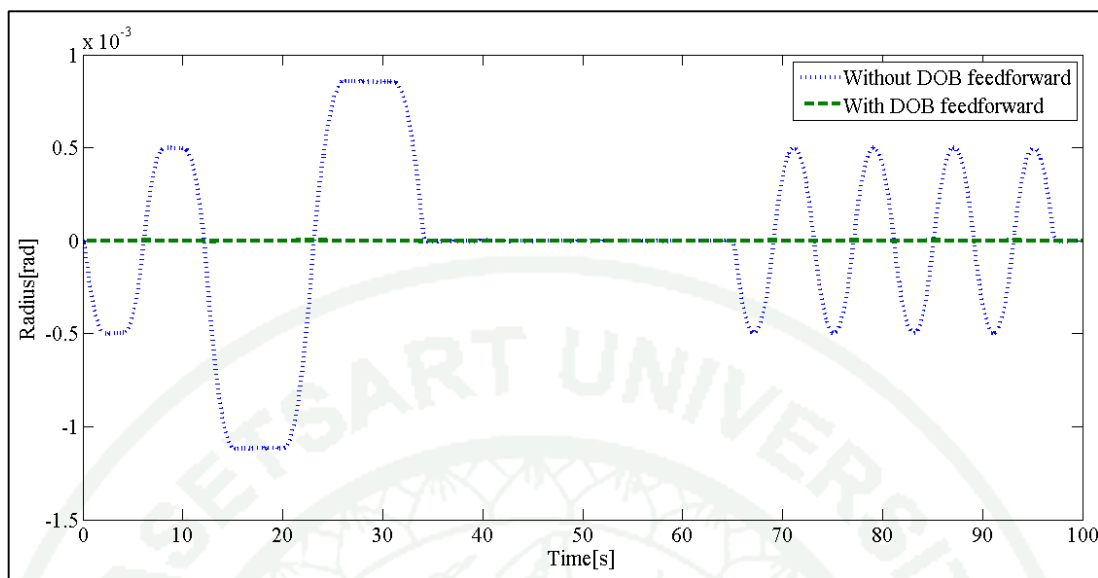
## 1.2 Result



**Figure 18** Force estimated by disturbance observer

Figure 21 shows the comparison force response between external force and force estimation by disturbance observer. As shown in the simulation result, a disturbance observer can be used to estimate the external force without force sensor.

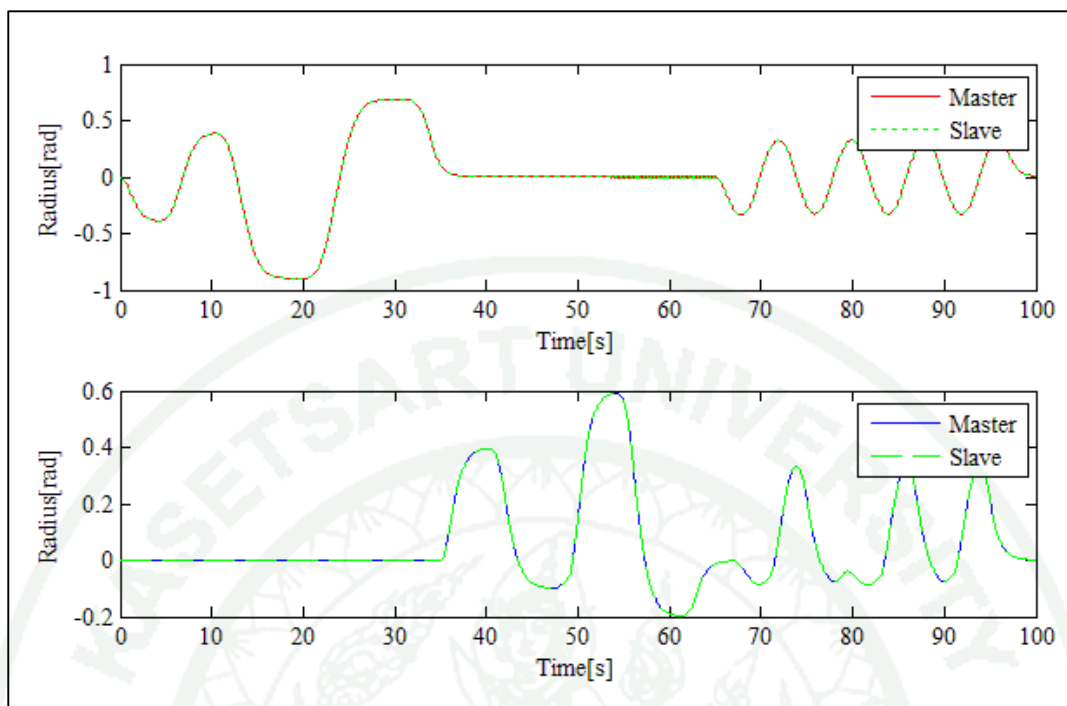
Therefore, disturbance observer is good candidates which can be solving the disadvantage of force sensor.



**Figure 19** Error of position, comparison with/without disturbance loop

The comparison of the position response between the conventional and the proposed method with feedforward DOB compensation are shown in Figure 22.

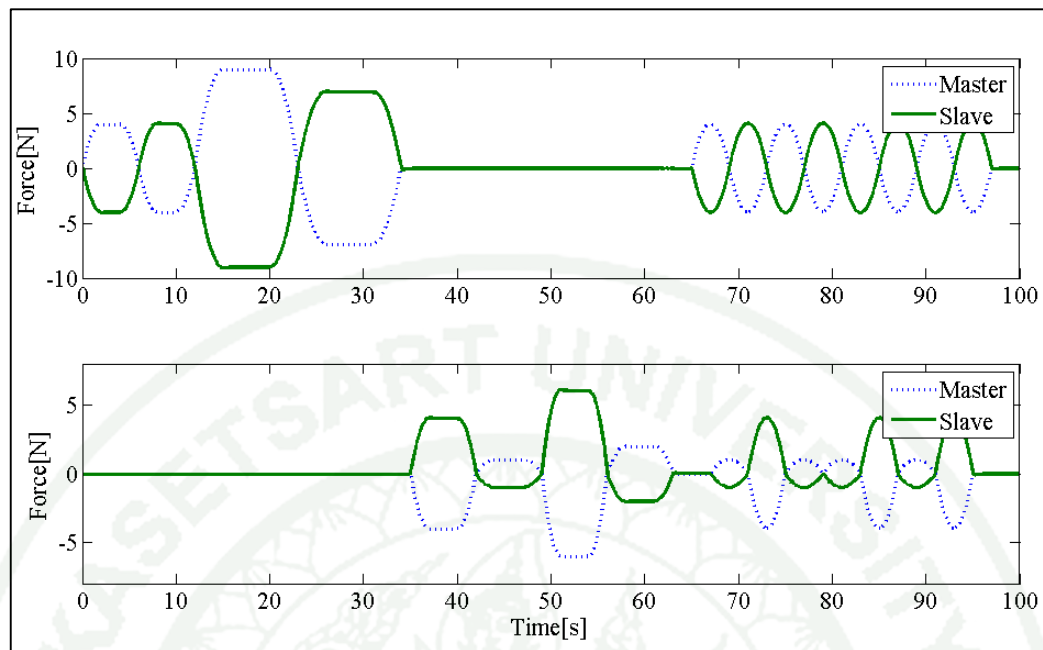
An error position response of the propose control method with feedforward disturbance compensation is can be reduced. Moreover, the high robust force control loop can be obtained.



**Figure 20** Position response at master and slave of two joint of the robot system

Figure 23 shows the position responses between master and slave side based on bilateral control. The position response at the slave side can be tracked almost identically over the position response at the master side.

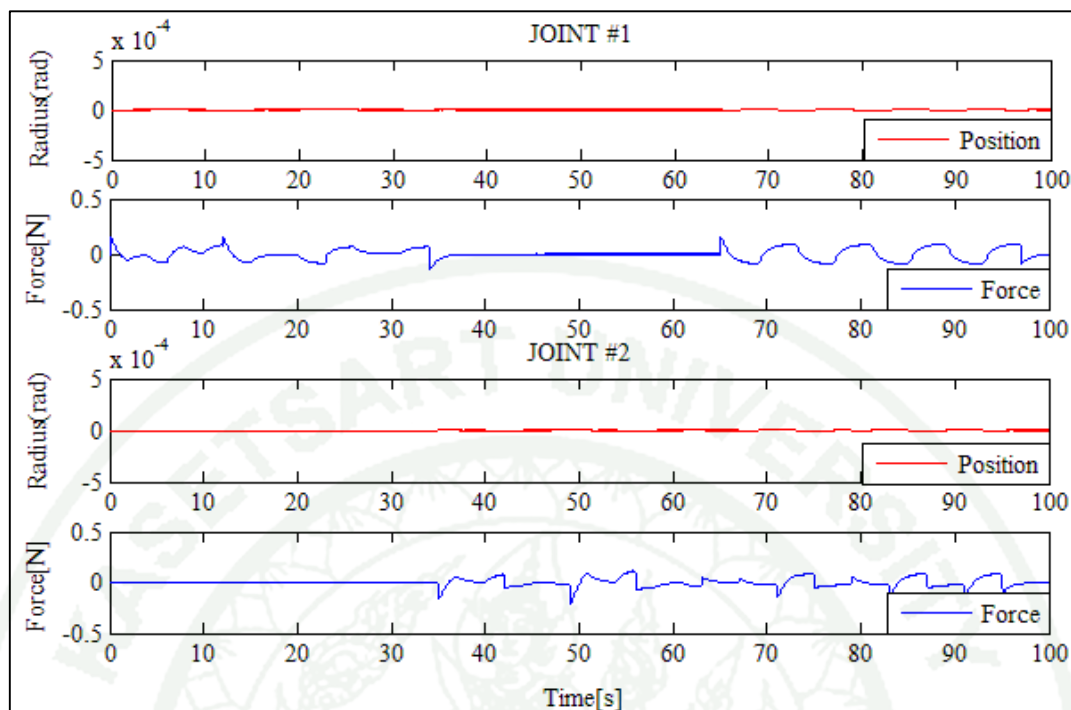
The target of the position control loop of the bilateral control can be achieved. As shown in the results, the erroneous change of position is reduced to zero.



**Figure 21** Force response at master and slave of two joint of the robot system.

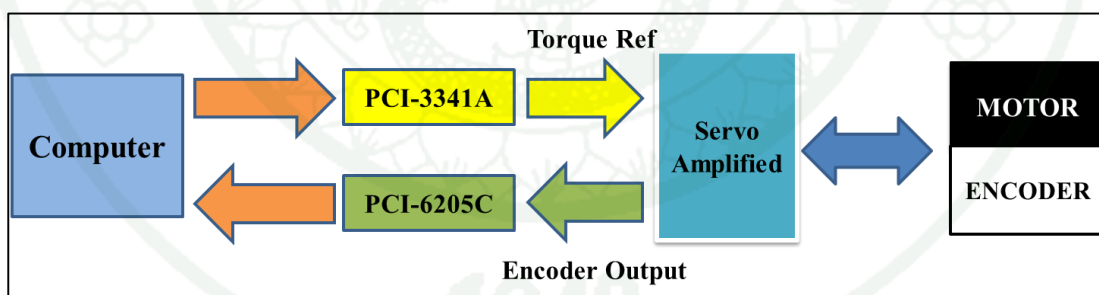
Figure 24 shows force response between master and slave side of robot system based on bilateral control. The upper picture represents first joint and lower picture represents second joint of the robot system. The force responses at the slave side sense by DOB is opposite direction with respect to the force response at the master side. It confirm the second target of bilateral control, can be obtained to the Newton's law (Action = Reaction).

As shown in Figure 25, the position response in the differential mode and the force response in the common mode can be tracked almost identically over the position and force command which can be set to zero value.



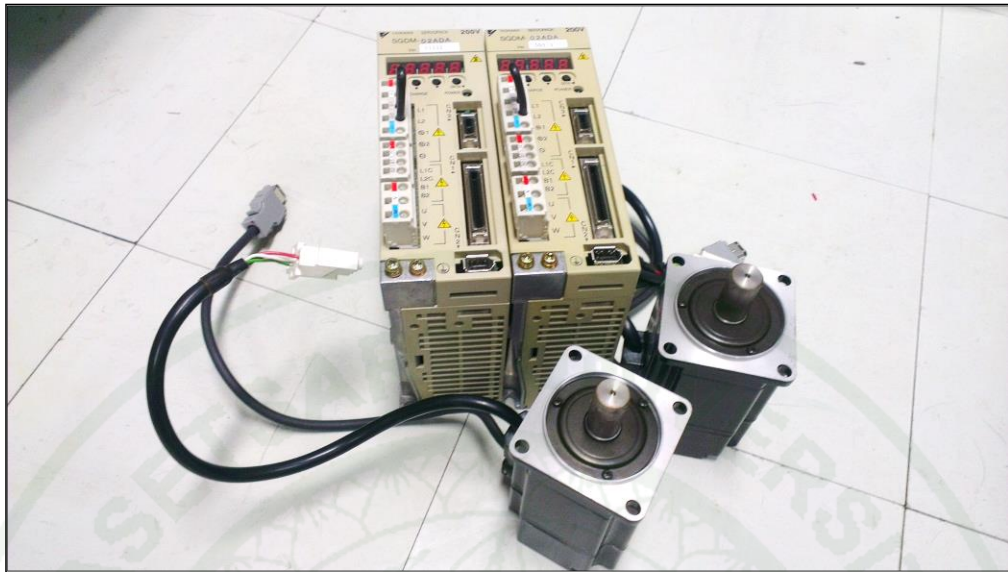
**Figure 22** Different of position between master/slave and summary of force between master and slave

## 2. Experimental



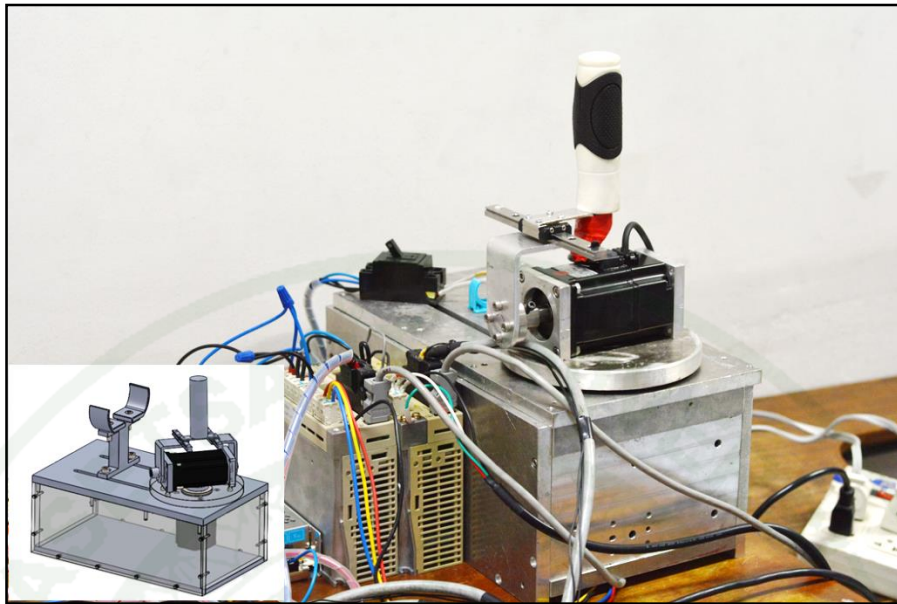
**Figure 23** An overview of equipment connection for once actuator.

Experiments are performed with two degree of freedom manipulator. Control software is written in C language under RT-Linux (red hat 9.0). Sampling time is 0.1 millisecond with a computer pentium4 processor, ram 1GB and hard disk 80GB. The computer is equipped with Input encoder-pulse counter board, interface card PCI-6205C, and digital to analog output, interface card PCI-3341A. Figure 26 presents an overview of the equipment connection for once actuator in the robot system.



**Figure 24** Servo motor and amplified

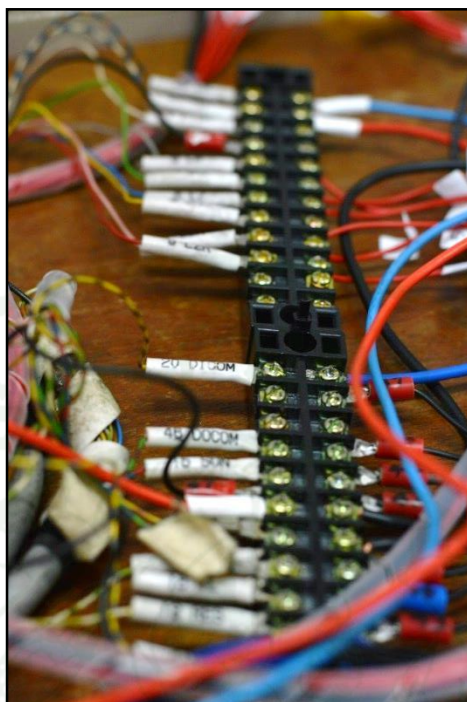
Figure 27 shows Yaskawa ac servo motor 220 Volt, 400W with Peak torque at 1.91 Nm. It has implemented on wrist rehabilitation robot system follow proposes design. The robot system has designed on aluminum material for strength and lightweight. Moreover, the robot system is use to rehabilitation. It should have more accessory for supported to the user. This thesis has glove with Velcro tape, arm holder supporter and another hand tools for more choice to rehabilitation, represent on Figure 28 and 29.



**Figure 25** An experiment following a robot design.



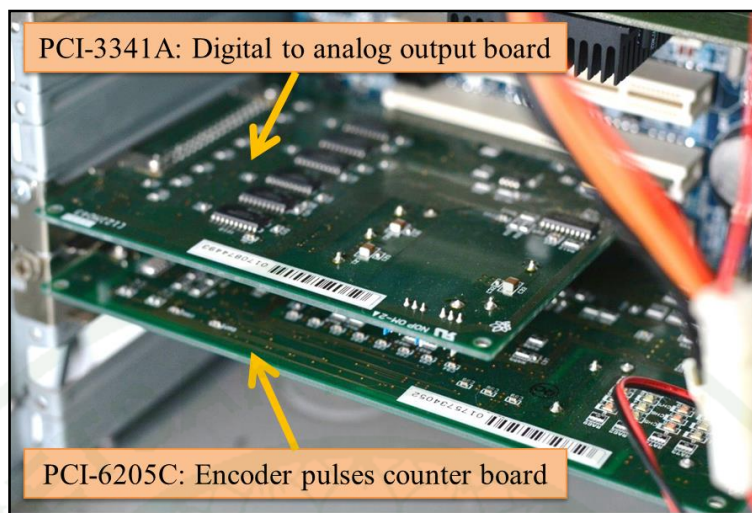
**Figure 26** Supporting tools of the robot.



**Figure 27** Wiring circuit.



**Figure 28** Desktop computer with pentium4 processor.

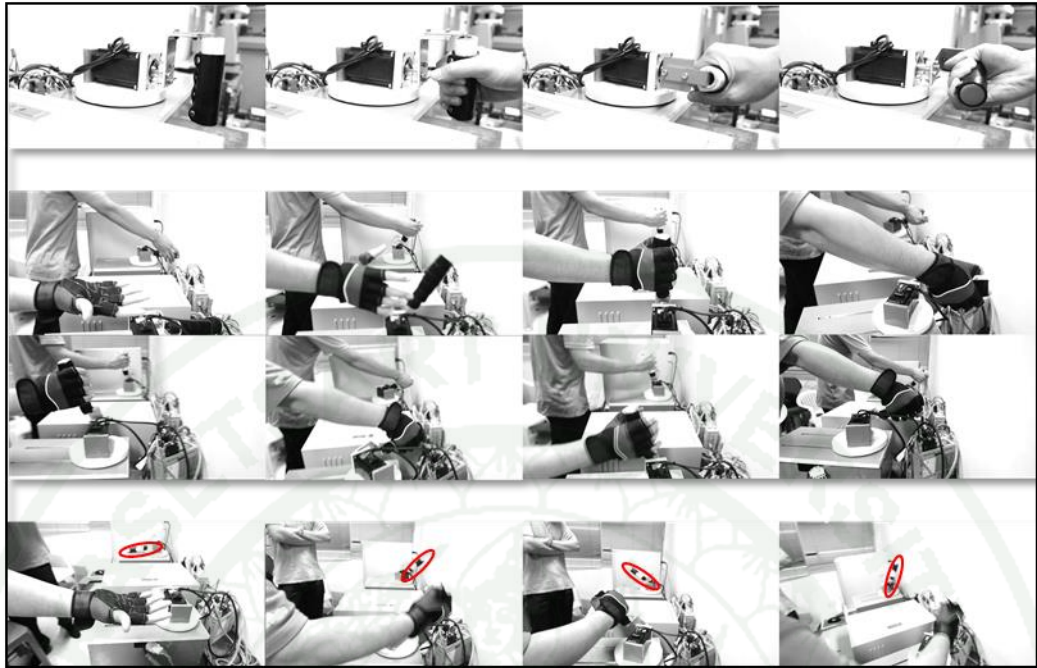


**Figure 29** Interface card of PCI 2504 and PCI 3346A.

Figure 30, Figure 31 and Figure 32 show an overview of wiring and controller of the robot system. First step of bilateral control based on disturbance observer has tested by cable operation between master side and slave side for wrist rehabilitation robot system.



**Figure 30** Operation of wrist rehabilitation robot system.

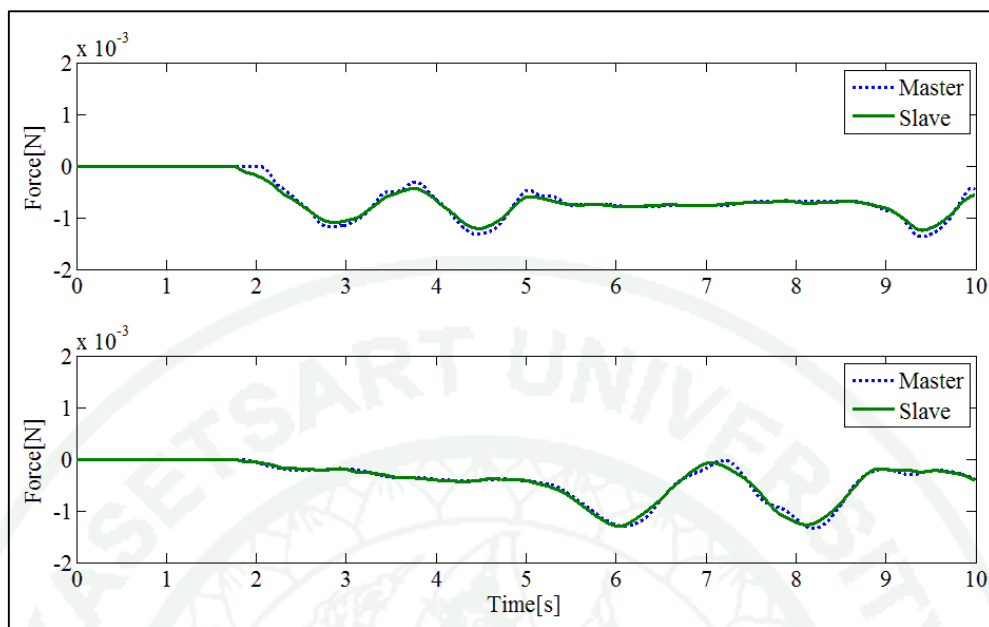


**Figure 31** Snap shot of VDO robot operating.

This figure shows VDO snapshot, consists of second hand tools operating, bilateral mode and one side user bilateral mode. The robot system with a bilateral control operating can transfer force and position between the master side and slave side with real-time control.

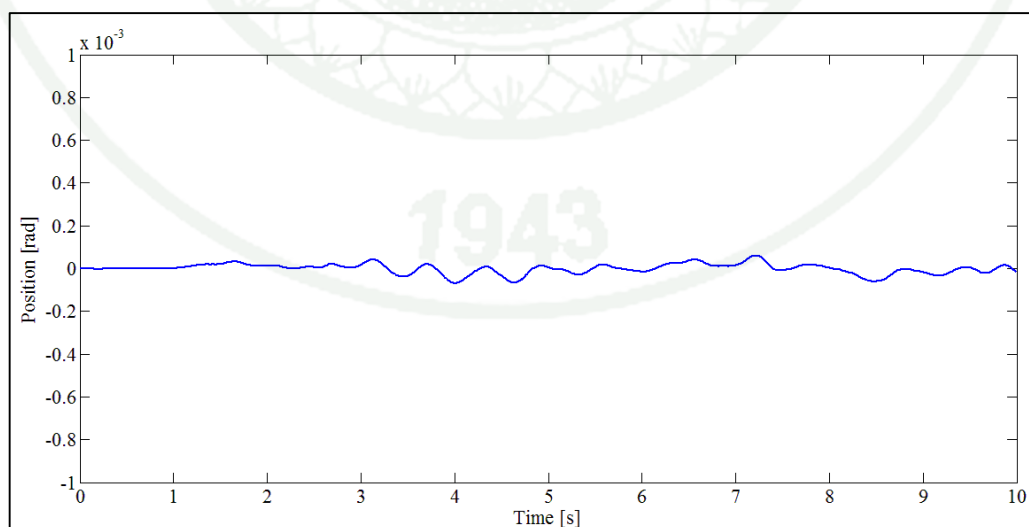
From the experimental results, a high performance of the position and force control can be achieved by applying the proposed disturbance observer and bilateral control method.

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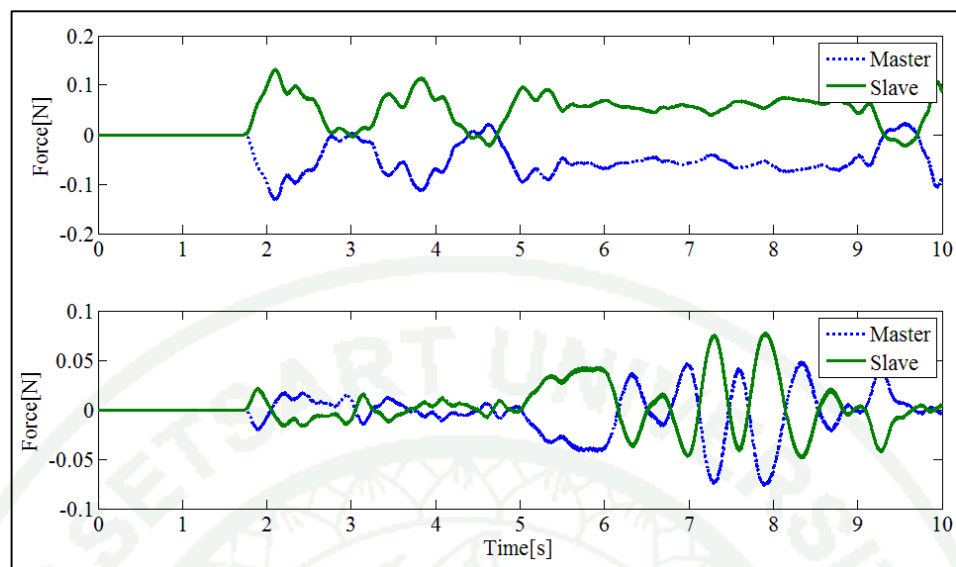


**Figure 32** Position response of bilateral control with an experiment.

Figure 35 shows a position response between master side and slave side based on bilateral control with a real experiment. The slave robot can tracked almost identically over the position response at the master side. The result confirms an ideal of bilateral control of  $\theta_M - \theta_S$  should be zero. It has shown in Figure 36.

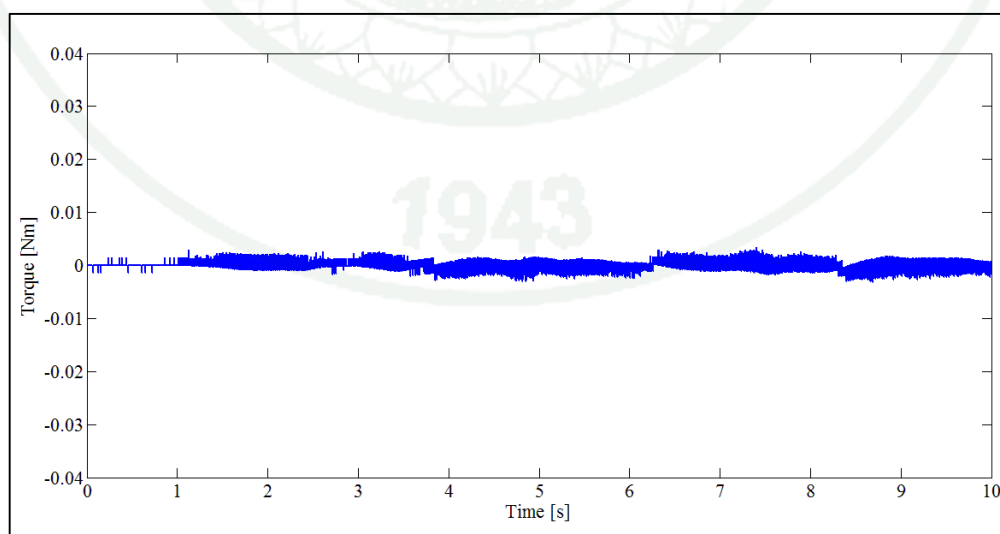


**Figure 33** Position error response of bilateral control with an experiment.



**Figure 34** Force response of bilateral control with an experiment.

Figure 37 represents force response between master side and slave side of wrist rehabilitation robot system which is controlled by bilateral control based on disturbance observer. The force response at slave side is in opposite direction with respect to the force response at the master side. The result confirmed follow a Newton's law "Action = Reaction" or  $\tau_{Ml} + \tau_{Sl}$ . Its value should be zero as shown in Figure 38, and confirm a disturbance observer can estimated external force for wrist rehabilitation.



**Figure 35** Summary force response of master/slave with an experiment.

## Discussion

In this study, the haptic technology has a limitation with force sensor, for instance, force sensor has limitation imposed on bandwidth, and force sensor can measure on point of sensor. The high performance sensor is very expensive. This robot is the best solution with using disturbance observer method. It can be replaced the force sensor, for the high resolution, fast response and lower cost.

Future more, the target to build a robot as a medical tool which is work to transmit movement of wrist between physical therapists and patient. The control loop should be real-time and best response feedback of force and position. A good candidate control method is bilateral control which transforms of position and force into acceleration dimension and controlled similarly at the same time.

Moreover, mechanical design complete on solidwork 3D programming which followed recommendation from research papers and applied a supporting accessory. And 90 percent completed with a test-rig version.

Lastly, prototype version of wrist rehabilitation robot system is controlled by bilateral control based on disturbance observer. It has tested in the CMIT laboratory member.

## CONCLUSION AND RECOMMENDATIONS

### Conclusion

This thesis has presented detail of the design and implementation of wrist rehabilitation robot system. That supported on two revolute joint corresponding wrist flexion/extension and radial/ulnar deviation. The design focused on developing a mechanically robust, safe and easy to use device. The control method is using bilateral control based on disturbance observer. This thesis has not begun clinical testing with the robot system because this is prototype version.

Disturbance observer can estimate an external force without force sensor. It has confirmed a good candidate by Matlab simulation result which can be solving the disadvantage of force sensor. Therefore, the force control loop implemented as feedforward is stable control for disturbance force compensation.

Bilateral control system can control position and force, which an ideal of the same position and action-reaction force. It can implement on wrist rehabilitation robot with a test-rig version. But parameter gain should be identifying again with a real-experiment such as inertia moment, P control and PD control.

Mechanical design for prototype version is good movement, balance and strong. But for the future version, it should change the base material and wiring circuit.

## Recommendations

Future work separate in 3 parts of communication, robot system design and to improve performance of control system.

1. This thesis is started on wiring operation for wrist rehabilitation robot based on bilateral control. The telecommunication will apply in the system such as wireless device.

2. The prototype robot version with simple design is not interested in the patient. In the future, it should design an appropriate robot system for the patient such as APPARATUS V2.

3. In rehabilitation, the rehabilitation robots must have high accuracy and correct rehabilitation movement to reduce injury of the patients. The recommendation of physiotherapist is important to design the controller of robots. So, the particle filter is used in this control system to improve accuracy and precision of the whole system.

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