SKILL EVALUATION IN HUMAN ADAPTIVE MECHATRONICS. BIMANUAL OPERATION WITH X-Y STAGES

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Abstract. In this paper, some HAM (Human Adaptive Mechatronics) research results on operator skill evaluation, operation assistance, identification of operator's dynamics, skill acquisition, and coupling phenomenon in bimanual operation are presented at first. Then the bimanual operation is discussed in detail. The phenomenon of spatial coupling between two different tasks performed by two hands respectively (bimanual operation) and the effect of frequency ratio and phase-lag between two circle tracking tasks on the bimanual operation are investigated in this paper. Two XY-stages developed in Tokyo Denki University are used as human-machine interfaces, with which various experiments on human bimanual cooperative operations have been conducted to investigate the human operation characteristics for the development of human adaptive mechatronic systems. In this paper, three experiments of bimanual operation are presented, with which the phenomenon of spatial coupling was clearly observed. It was also found in the experiments that the human operator can develop his/her skill of bimanual operation much easier with some frequency ratio and some phase-lag.

Key words: spatial coupling, skill acquisition, bimanual operation, XY-stage, haptic system, operation assisting, human adaptive mechatronics.

1. INTRODUCTION

As a synergistic integration of electronics, mechanics, system sciences, control engineering, information technologies and other key technologies, the mechatronics has been improving the quality of human life. To use a mechatronic system effectively when a human operator is involved in the system, the operator should be skilled. Otherwise the mechatronic system should be able to assist the operator properly according to his skill level by providing necessary information, rules, and knowledge. In this way, the operator can learn and improve his skill and

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knowledge, and then can manipulate the system without any mis-operation even in complex and/or abnormal situations.

Such mechatronic system which adapts to operator skill and assists to enhance it, is defined as Human Adaptive Mechatronics (HAM) [36, 25, 49]. It consists of Mechanism, Electronics, Computers, Systems and Control, and Human Sciences as depicted in Fig. 1.
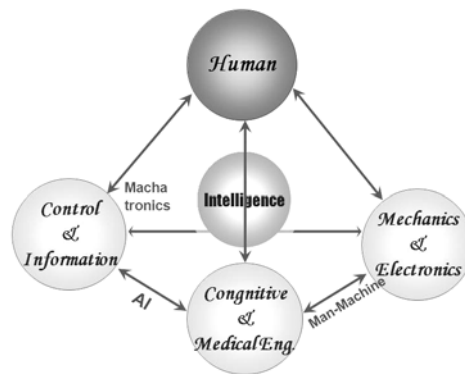

Fig. 1 – Diagram of human adaptive mechatronics.

A HAM system should know the operator's skill level so that proper assistances can be provided to the operator and then the operator can enhance his skill with the assistances. In Tokyo Denki University (TDU), we have designed HAM systems to identify the operator's dynamical model [46, 51], evaluate the operator's skill level [42, 50, 47, 45], provide assistances based on the operator's skill level [42], and assist to enhance the operator's skill [43]. In bimanual operations, the skill level can be evaluated by the coupling or decoupling information between two hands [50, 47, 45].
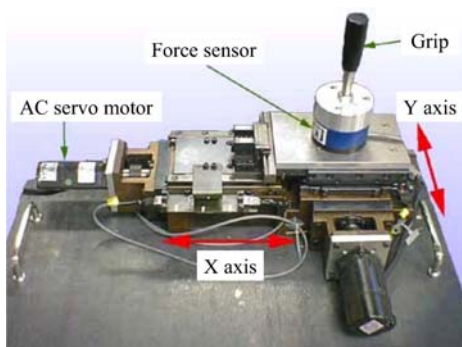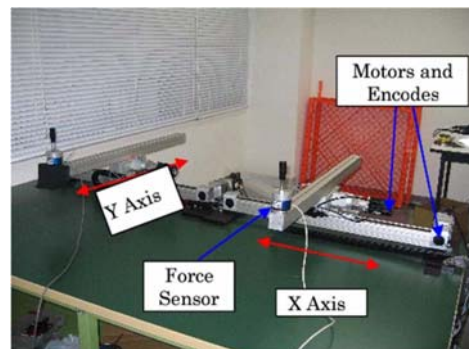

Fig. 2 – Single X-Y stages.   Fig. 3 – Double X-Y stages.

The phenomenon of coupling between tasks performed by two hands respectively has been observed and studied since 1980s [14, 12, 15, 4, 33]. It has been found that there is a strong tendency for the movement of one hand to become more similar to the movement of another hand in any bimanual tasks, including different tasks for two hands and same tasks with different phase (Anti-phase or with phase-lag) for two hands [50, 14]. The coupling affects the human operators' operation skill and/or limits improving the skill in bimanual operations. An X-Y stage shown in Fig. 2 has been used in TDU for the research on HAM, with which we have developed HAM systems for assisting control, operation skill acquisition, identification of operators' dynamics.

For the research on the bimanual operation, two X-Y stages shown in Fig. 3 have been designed in TDU [39], where each X-Y stage is equipped with two DC motors, a six-dimension force sensor, and two encoders. A human operator can move the X-Y stage through a grip equipped the force sensor. A PID controller is designed such that the X-Y stages can follow the trajectory given by the human operator's operation, including the position and force commands. The parameters of the PID controller were adjusted by measuring the response of the controlled X-Y stage dynamics. As a human-machine interface, or an input device of a haptic system, the X-Y stage provides an interface for the human operator such that the operator's operation commands, including force, position, and velocity commands can be acquired and then be used as input signals to control a mechatronic system.

In [28], a haptic control system structure that executes estimating of the human's skill and assisting him was shown based on a concept of human-adaptive-mechatronics (HAM). The guess of the human's operational characteristic is done by identification of human's dynamics with simple transfer function in real time. The assisting control is achieved by changing the ratio of an ideal machine operation and human's operation. The strategy proposed in [35] consists of an identification of an operator's control characteristics and an automatic tuning of dynamic property of the machine. The tuning is done by changing impedance parameters of a virtual internal model (VIM) for the machine. An update law of the tuning is done by utilizing Lyapunov function. It was shown [19] that in the control system design of the teleoperation based on VIM, slave systems with different dynamics could be controlled by the master-device with same dynamics.

In this paper, some HAM research results in TDU about operator skill evaluation, operation assistance, identification of operator's dynamics, skill acquisition, and coupling phenomenon in bimanual operation will be presented at first. Then the design procedure of X-Y stages will be given. Three experiments of bimanual operation conducted with the X-Y stages will be described. Three right-hand health male students participating in this research were asked to operate two X-Y stages to track reference trajectories on a line and a circle respectively in the first experiment, to track reference trajectories on two circles with two X-Y stages respectively with different frequency ratio in the second experiment and with

different phase-lag in the third experiment. Based on the experimental results, some observation will be discussed.

The arrangement of the paper is as follows: Section 2 presents some HAM research results in TDU; Section 3 designs X-Y stages; Section 4 describes the experiments conducted with X-Y stages; Section 5 shows experimental results and gives observation results; and Section 6 concludes the paper.

2. RESEARCH RESULTS ON SKILL EVALUATION AND ASSISTING CONTROL

2.1. IDENTIFICATION OF DYNAMIC CHARACTERISTICS IN HUMAN OPERATION [46]

The mathematical model of the human operation studied since long time before [2] includes the various psycho-physical limitations inherent in the human operator. Kleinman and others [3] studied the dynamic characteristics of pilots as the control function point of view. McRuer [5] identified the operator dynamics as the linear combination of the proportional and derivative times the delay. Miall *et al.* considered that the human operator works as a Smith Predictor to compensate the time delay of the controlled object [13]. Furuta *et al.* proposed that the skilled operator is constructing the reference model in a certain interval and skill can compensate the lacked information [32].

In this research, the operator dynamic characteristics are identified for developing the assisting control system with considering various conditions including time delay and partially signal missing. The X-Y stage in Fig. 2 is used as a man-machine interface in the data acquisition for the identification of the human dynamics. The operator watches the display showing the positions of the reference disk and the operator disk. The operator disk on the screen moves according to the X-Y stage position. When the reference disk moves circularly or horizontally as shown in Fig. 4 and Fig. 5, the operator manipulates the X-Y stage to let the operator disk follow the reference disk.

The X-Y stage shown in Fig. 2 is used for the human-machine interface, which is controlled to behave like a mass-damper dynamics with given parameter values. The operator holds the grip and manipulates it during the experiment. The force applied to the grip is measured by the force sensor and he operates the X-Y stage with the second order mass-damper dynamics. By the choice of the mass-damper parameters, the reaction feeling in the operation can be adjusted.

The operator, the display and the X-Y stage are shown in Figs. 6 and 7. The X-Y stage is placed at three different positions; in front, 10 cm right and 20 cm right positions. The dynamic difference due to the relative position between the

operator and the X-Y stage is studied by the frequency response. The X-Y stage is controlled by the internal model represented by three different mass-dumper-spring parameters so that the effect to the different dynamics can be studied. Three different systems are used for the virtual internal model (VIM).
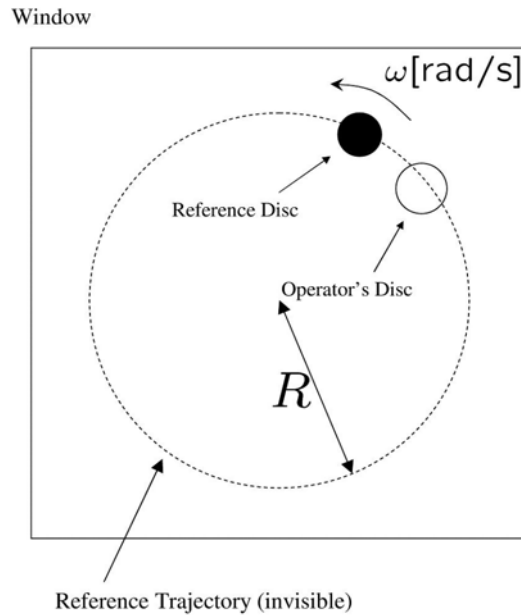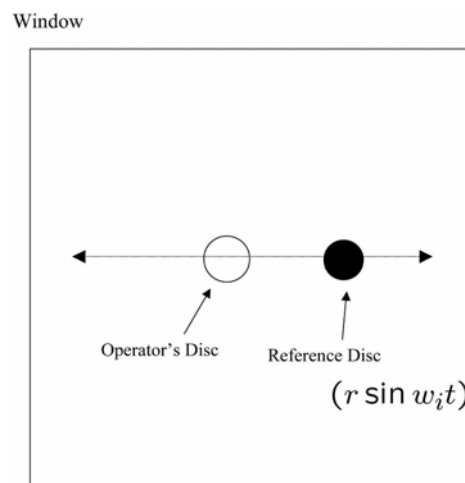
Fig. 4 – View Screen (circular motion).

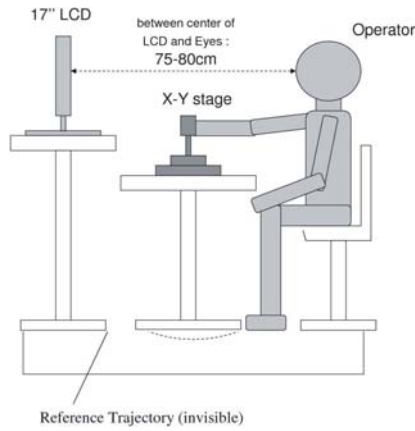Fig. 5 – View Screen (linear motion).

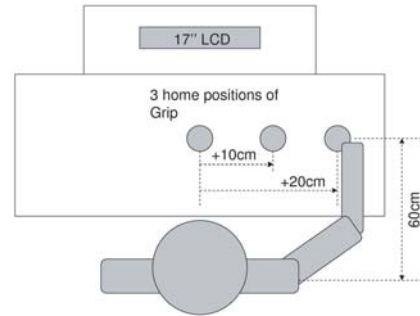Fig. 6 – Environment (side view).   Fig. 7 – Environment (top view).
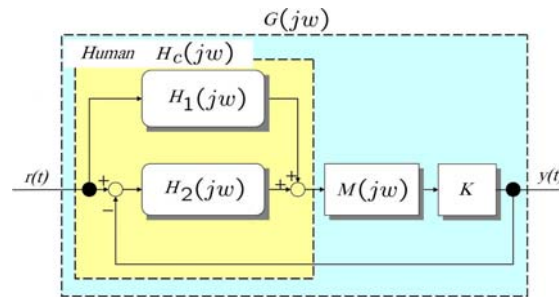

Fig. 8 – Block diagram of Kawato Suzuki model.

Denote the transfer function of the human-machine interface by $M(j\omega)$, which is controlled to match to the mass-spring-damper model according to the VIM control method [11], and the gain by K. The operator is supposed to have a control structure similar to Kawato-Suzuki-Ito model shown in Fig. 8, which has the feedforward transfer function $H_1(s)$ and the feedback one $H_2(s)$.

The frequency characteristics of the total operator and machine combined system $G(j\omega)$ is determined by

$$G(j\omega) = \frac{(H_1(j\omega) + H_2(j\omega))M(j\omega)K}{1 + H_2(j\omega)M(j\omega)K}.$$

It is assumed that the operator dynamics including the feedback $H_c(j\omega)$ is represented as

$$H_c(j\omega) = \frac{H_1(j\omega) + H_2(j\omega)}{1 + H_2(j\omega)M(j\omega)K}.$$

The total transfer function $G(j\omega)$ can be re-written as

$$G(j\omega) = H_c(j\omega)M(j\omega)K.$$

The frequency characteristics $H_c(j\omega)$ is considered as the operator frequency characteristics. The identification of the operator frequency characteristics gives $G(j\omega)$, from which $H_c(j\omega)$ can be determined since the dynamics of human-machine interface is known. The identified results show that $G(j\omega)$ is equal to 1 over a certain frequency band. Thus $H_c(\omega)$ gives the inverse characteristics of the machine, which is said usually the human dynamic characteristics. It is also found from identified results that the human operator adapts to the variation of the human-machine dynamics so that the dynamics of the total system does not change as far as he can afford to adapt to the change of the controlled system dynamics.

The identified transfer functions $H_1(j\omega)$ and $H_2(j\omega)$ of the human operator are shown as Figs. 9 and 10 for unskilled and skilled operators, respectively.
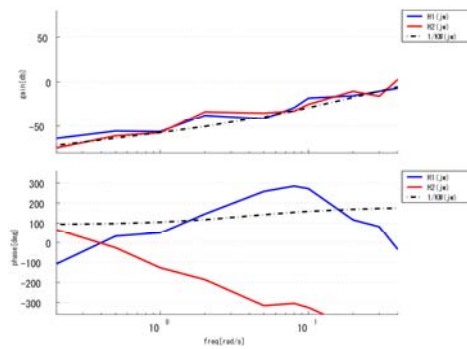

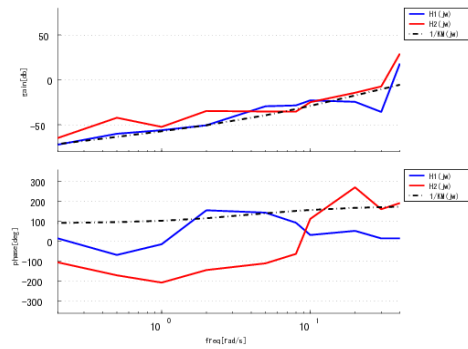Fig. 9 – Bode plot of unskilled operator.   Fig. 10 – Bode plot of skilled operator.

2.2. ASSISTING CONTROL IN HUMAN ADAPTIVE MECHATRONICS – SINGLE BALL JUGGLING [42]

In [3], it is considered that the reference for the operation is given. During the operation, however, the operator should generate the desired trajectory from the available information. The human operation is successful if the proper reference is generated and is tracked by the controlled variable. To get skill of the operation, a human operator learns through the practice assisted by a teacher who corrects the operation by the additional force if the operator's manipulation is not appropriate. Such assistance in the learning stage is found in many places such as driving vehicles and others.

An example of operations requiring the skill may be the juggling of the multiple objects, where the operator watches the movements of the objects and synchronizes the manipulation by hands. In [42], we have developed a single ball

juggling system, which swings up repeatedly a golf ball. The ball connected by string to a fixed place is hit by a slider at the bottom of swing as shown in Fig. 11. The string connected ball can be considered as a pendulum [25]. An assisting system shown in Fig. 13 for the operator has been developed.
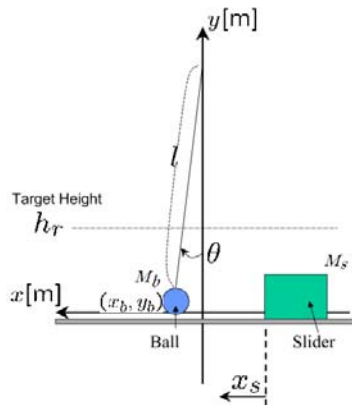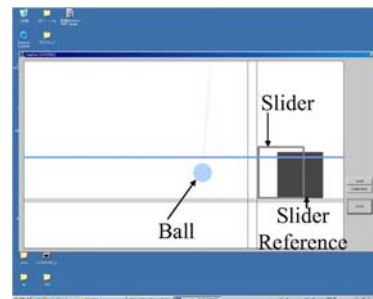

Fig. 11 – Model of juggling system.

Fig. 12 – Screen image for juggling.

The position of the slider is controlled by the X-Y stage (shown in Fig. 2) manipulated by an operator. The operator looks at a screen where the position of the ball, the reference position of the slider and the actual position of the slider are displayed as shown in Fig. 12.

The block diagram of the control system is schematically shown in Fig. 14, where the close of the sampler switch denotes the impact of the slider against the ball.
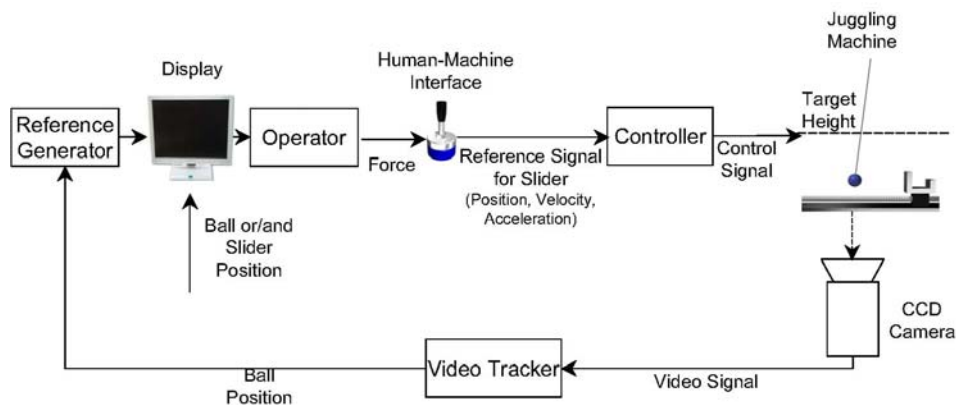

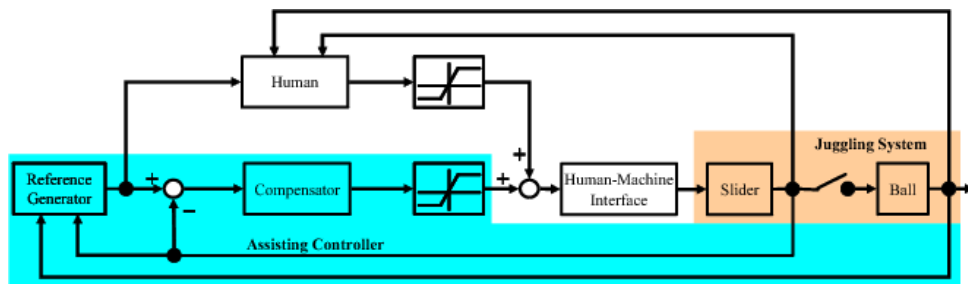Fig. 13 – Juggling assisting control system.

Fig. 14 – Block diagram of control.

The assisting control system is designed so that the system works smoothly in the presence of the false operation which may be considered as the disturbance to the control system. To design the assisting control system, the reference motion of the slider should be determined [26, 27]. The slider moves according to the command of the X-Y stage manipulated by the operator. The assisting control system includes Kawato-Suzuki Type model for the voluntary motion of muscle [8, 9] as shown in Fig. 14, where the off-set to the compensator may indicate the skill level and by measuring this error the operator skill level may be evaluated.

The X-Y stage is used for the human-machine interface, which is controlled to have the mass-damper dynamics with given parameter values. The operator holds the grip and manipulates it in the experiment. The force applied to the grip is measured by the force sensor and he operates the X-Y stage whose dynamic relation between the position and the applied force is controlled to satisfy the second order mass-damper system VIM. By the choice of the parameters of mass-damper, the feeling in the operation can be adjusted. Then the controller for the corrective force of the teacher's role is designed so that the virtual position in VIM tracks the given reference of the slider. The slider is controlled to follow the position of X-Y stage.

In the designed assisting control system for this juggling operation, the operator and the assisting forces are additionally applied to the grip of the X-Y stage. Either assisting control system or an operator can alone juggle the ball. The total assisting system consists of two parts; one is the reference generation from the ball motion and the other is controlling the X-Y stage to assist the operator.

Letting the transfer function of the human-machine interface be controlled to match the VIM, the transfer function of the teaching part can be designed properly for VIM. By the proper choice of the limiters for the applied forces by the assisting system and the operator, the operator can be properly assisted.

With the designed system, the juggling operation is tried by changing the reference ball height. One of experimental results is shown in Fig. 15.
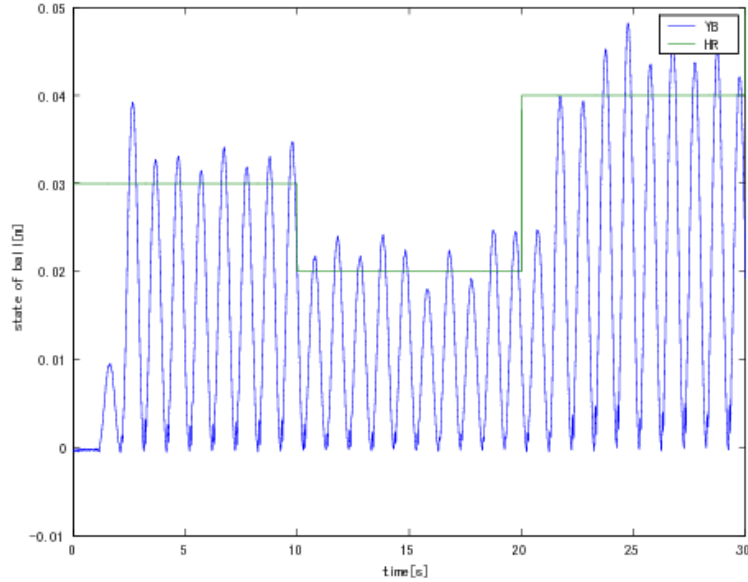
Fig. 15 – Ball's position and reference height.

2.3. CONTROL SYSTEM FOR SKILL ACQUISITION – BALANCING PENDULUM BASED ON HUMAN ADAPTIVE MECHATRONICS [43]

An assistance system with force feedback for skill acquisition has been developed in TDU [43]. In this system, the operation task is to balance an inverted pendulum on a cart. For that purpose, a virtual pendulum that is calculated real-time with computer graphics is developed. A human operator manipulates an X-Y stage as the human-machine interface with haptic function to balance the pendulum. An assistant controller is designed based on the Kawato-Suzuki model shown in Fig. 16 [8, 9]. In this model, it is proposed that the progress of the skill may bring the increase of feedforward and reduction of feedback actions.
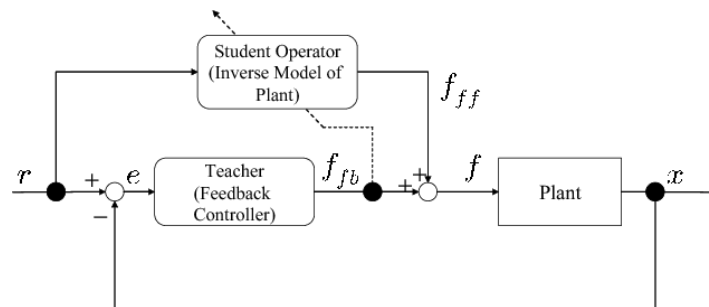

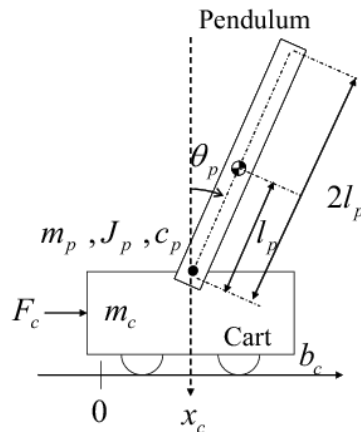Fig. 16 – Architecture of teaching based on Kawato-Suzuki model.

Fig. 17 – Model of the inverted pendulum on the cart.

A "student operator" directly operates the plant in the feedforward way and if there exists the error between the reference and output, teacher correct the operation by the correcting force based on the error. If the error vanishes, the student can operate desirably. And he can develop the inverse model of the plant by himself. Thus the student can learn appropriate force for the operation by a teacher's force. If the inverse model is completely developed, the teacher's force does not generate.

The pendulum and the cart are schematically shown in Fig. 17. The position of the cart is controlled by the command from the man-machine interface manipulated by the operator, where the X-Y stage shown in Fig. 2 is used as the human-machine interface.

The operator gets the information of the angle of the pendulum and the position of the cart through the screen as shown in Fig. 18. The scene of the experiment system is shown in Fig. 19. The block diagram of the control system is schematically shown in Fig. 20, which is based on VIM to make the bilateral control system [11].

The forces from the operator and the controller are additionally applied to the grip of the X-Y stage. By the help of assistance control system the operator can balance the pendulum even when he has not the skill. By the proper choice of the upper and lower bounds of the applied force for the assisting system and the operator, the operator can be properly assisted. To design the assisting control system, a reference is determined at first. In the system, there are three controllers, *i.e.*, the assistance controller, the VIM following controller for the X-Y stage and the VIM following controller for the cart. Evaluation experiments with and without assisting force were performed. The results show that the virtual inverted pendulum can be well-stabilized by a human operation and the assist control when the

operator was trained through the testing with the assisting force. It was confirmed in the experiments that the human operator had acquired the skill after training with the proposed assist method.
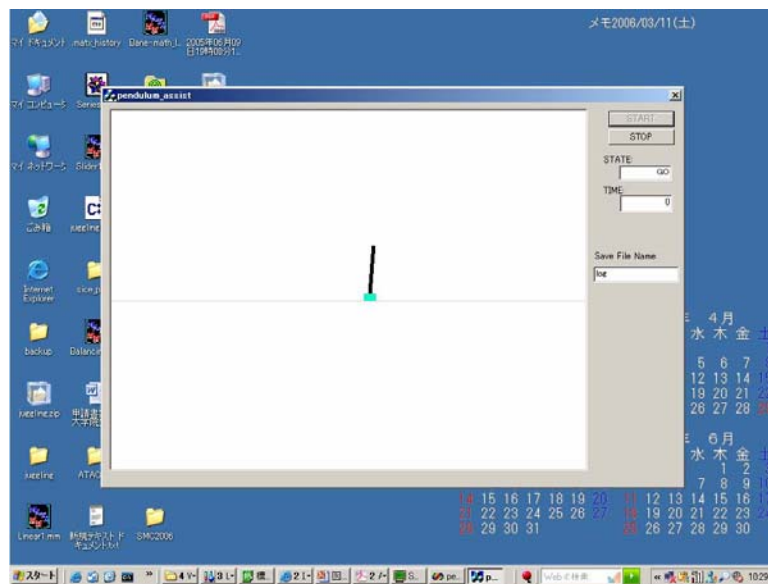

Fig. 18 – Information on the screen.
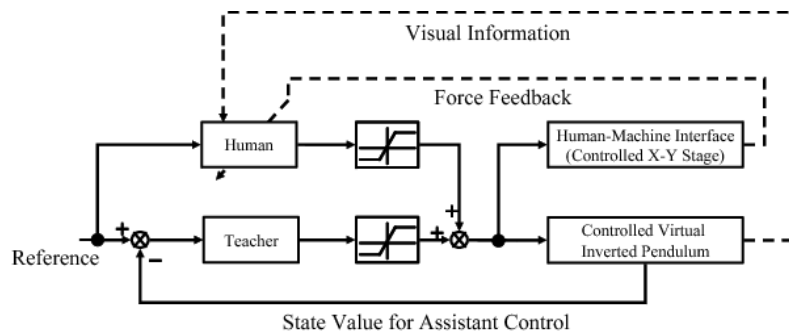

Fig. 19 – Scene of environment.

Fig. 20 – Block diagram of control.

2.4. CAPSUBOT [44]

As one of HAM research results in TDU, a capsule type robot named capsubot, shown in Fig. 21 has been developed. The robot has no moving part outside its body, no legs, no wheel. Its motion is purely based on its internal force and friction with the environments.

Fig. 21 – Capusbot developed in TDU.

The capsubot is a two mass system. It consists of a capsule shell m_1 and a cylinder mass m_2. The internal force between the shell and the cylinder is generated using permanent magnet and coil pair, which makes the cylinder mass move forward and backward inside the capsule shell.

To move the capsubot forward, a four step motion pattern [44] has been proposed as follows:

   I. Large backward accelerated motion of m_2, forward accelerated motion of m_1.

  II. Small backward decelerated motion of m_2, forward decelerated motion of m_1.

III. Small backward decelerated motion of m_2, m_1 remains stationary.

IV.   Forward slow motion of m_2, m_1 remains stationary.

Since the capsule robot has no external moving parts and can be made small in size, it has a large applicability in medical field, for example, as a self-propelled endoscope.

2.5. COUPLING PHENOMENON OBSERVED WITH NIRS IN BIMANUAL OPERATION [50]

The phenomenon of coupling between tasks performed by two hands respectively has been observed and studied since 1980s [14, 12, 15, 4, 24 30, 21]. It has been found that there is a strong tendency for the movement of one hand to become more similar to the movement of another hand in bimanual tasks, including different tasks for two hands and same tasks with different phase (Anti-phase or with phase delay) for two hands [14]. In this research, a NIRS, EGT-4000 Optical Topography System made by Hitachi Medical Corporation, Japan is used to measure the activation of the motor cortex in healthy subjects during bimanual and unimanual finger-tapping tasks.

It is said that only left or right side of the motor cortex area is active when a subject's contralateral hand (or fingers of the contralateral hand or the contralateral arm) is moving in a slow or normal speed. Thus in those tests with unimanual tasks, in general, only one side of the motor cortex area was paid attention [22]. In this research, both sides of the motor cortex area will be observed in unimanual operation to find the reason of the coupling between the left and right of the motor cortex areas for the bimanual operation especially when the subjects were asked to perform the bimanual and unimanual finger-tapping tasks as quick as possible. The relation between the coupling and the subjects' skill is also investigated.

In the experiments, subjects were asked to perform finger-tapping tasks in different patterns with two or all fingers of his left or right or both hands with visual instructions or with oral instructions.

As a typical result, Fig. 22 shows the concentration change of [HHb] while a subject was performing finger-tapping tasks with his left hand, right hand, and both hands, respectively. The red area indicates the high concentration in this area (Fig. 22).

It is clear from Fig. 22 that only right motor cortex is active for the left finger-tapping and only left motor cortex is active for the right finger-tapping in the low speed operation with the tapping period less than 0.4 second (Left Hand Operation) or 0.7 second (Right Hand Operation), and both sides of the motor cortex area become more active for quicker operation speed with the tapping frequency larger than 0.5 second (Left Hand Operation) or 0.6 second (Right Hand Operation). For a right-handed subject, much more activation in both sides of the motor cortex area can be observed in the finger tapping of left hand, and the

operation speed for both sides of the motor cortex area to become active is slower in the finger-tapping of left hand than the finger-tapping of right hand.
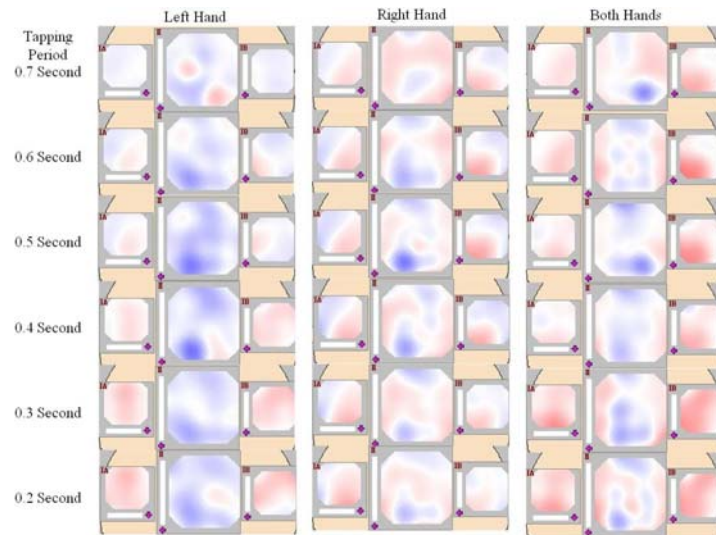

Fig. 22 – Change of [HHb] during two-fingers tapping with visual instruction.

Fig. 23 shows the concentration change of [HHb] when another subject was alternatively pushing two switches down with his index and middle fingers of both hands in anti-phase.

In the first and second trials, the strong activation in this subject's motor cortex area can be observed even with low operation speed. In the third and forth trials, the activation became weaker and weaker while the skill of the subject was enhanced more and more. The threshold speed with which the motor cortex area in bimanual operation becomes much more active increases with the development of the operation skill.

It is found in this research that not only contralateral side of the motor cortex area is active when a subject's right/left hand (or fingers of right/left hand or right/left arm) is moving in a high speed, but also the ipsilateral side of the motor cortex area. This reveals that the coupling between left and right motor cortex areas is the reason why the bimanual operation effects with each other. A higher move speed in bimanual operation results in more active in both side of the motor cortex area. And the threshold speed with which the motor cortex area in bimanual operation becomes much more active depends on the operation skill of the subject. Less coupling phenomenon in the right-handed subjects' right hand operation than the left hand operation is observed, which also explains the relation between the coupling and the operation skill because for right-handed subjects, they can control

their right hands much better than their left hands. The coupling phenomenon found in this research should be taken into consideration in the design of bimanual operation mechatronic system.
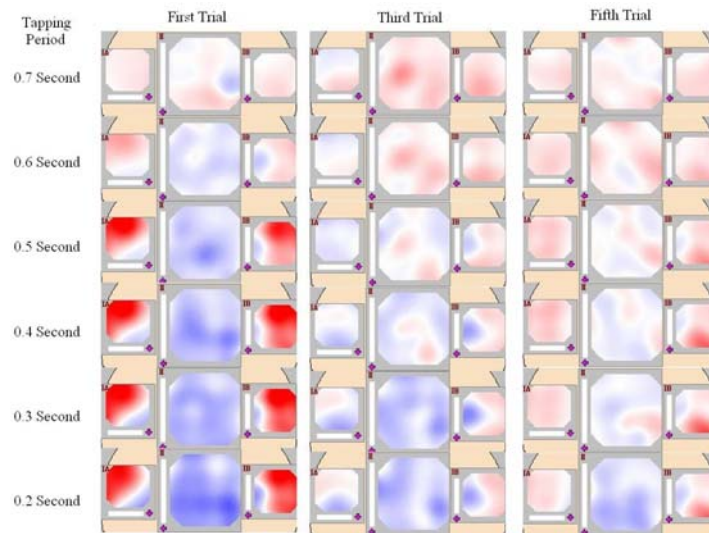

Fig. 23 – Relation between skill and change of [HHb] in bimanual operation.

2.6. DECOUPLING AND SKILL DEVELOPMENT IN BIMANUAL OPERATIONS [47]

It has been observed in our bimanual experiments with two X-Y stages that one hand motion affects another hand motion in bimanual tasks with high frequency, and the effect becomes weaker in lower frequency and for skilled operators [39]. The researches to analyze human bimanual motion have been done in the field of ergonomics [16]. The other researches have analyzed human dynamics from the control engineering point of view [28, 19].

In complex systems with several controlled variables, like robot manipulator or aircraft control, inputs are strongly coupled with outputs of the system. A decoupled control algorithm is often used so that each output or each degree of freedom of the complex system can be controlled separately [34]. In this research, this phenomenon is analyzed from the viewpoint of decoupling control.

In this research, two X-Y stages shown in Fig. 3 are used to construct a bimanual operation system. An operator manipulates two X-Y stages simultaneously by using both hands, to trace two periodic reference trajectories. The reference trajectories are displayed on the screen as inputs to human operator. The operator's hand positions are considered as outputs, and the transfer function of the human operator is identified from experimental data. The displayed reference signals on the plane are considered as the complex variables. This makes

the identification require less computation. The experimental set-up for the bimanual operation is shown in Fig. 24.
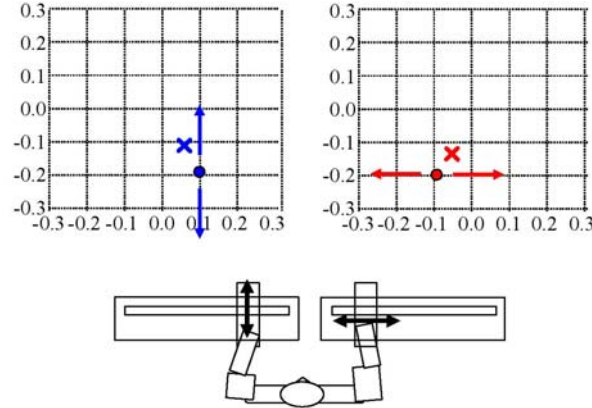

Fig. 24 – System configuration.

The reference and actual positions of X-Y stages are given to the operator as visual information on the projected display. The operator simultaneously manipulates two X-Y stages to follow reference points moving in different directions. The positions of X-Y stages are shown by "×" on the screen. A human frequency response is identified from the reference and the X-Y stage trajectories.

For the bimanual operation analysis, we consider both inputs (u_1, u_2) and outputs (y_1, y_2) (u_i, y_i $\in \mathbb{R}^2, i = 1, 2$) as the complex variables in $\mathbb{C}$. The x-axis components correspond to its real part and y-axis components correspond to its imaginary part. The reference inputs are

$$u(t) = \begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix} = \begin{bmatrix} jr\sin\omega t \\ r\cos\omega t \end{bmatrix},$$

where $u_1(t)$ is the reference position of right hand, $u_2(t)$ is the reference position of left hand. Let the right hand position be y_1 and left hand position be y_2, and they are the complex variables similar to the inputs. Thus, the actual positions of each operator's hands can be expressed as

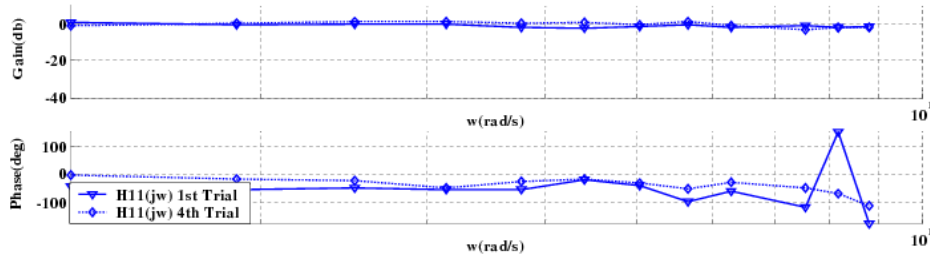$$y(t) = \begin{bmatrix} y_1(t) \\ y_2(t) \end{bmatrix}.$$

The relation between the input and the output vectors is

$$Y(j\omega){=}H(j\omega)U(j\omega)$$

$$H(j\omega){=}\begin{bmatrix} H_{11}(j\omega) & H_{12}(j\omega) \\ H_{21}(j\omega) & H_{22}(j\omega) \end{bmatrix},$$

where $U(j\omega)$ and $Y(j\omega)$ are the Fourier Transforms of the input u and output y, respectively. $H(j\omega)$ is the frequency transfer function between both inputs and two hand outputs.

From experimental data, the transfer functions are identified as shown in Fig. 25.

a)   left-hand reference to left-hand response $H_{11}(j\omega)$

b) right-hand reference to right-hand response $H_{22}(j\omega)$

c) left-hand reference to right-hand response $H_{21}(j\omega)$

d) right-hand reference to left-hand response $H_{12}(j\omega)$

Fig. 25 – Frequency characteristics of bimanual operation.
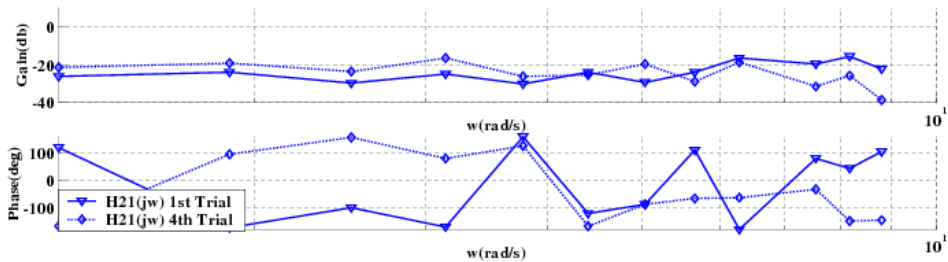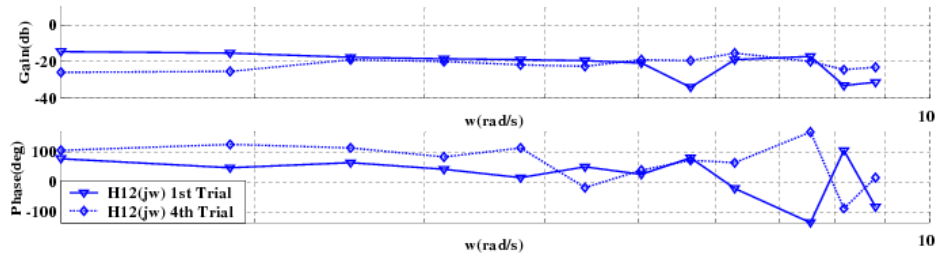
It is clear from Fig. 25a and b that the phase lags become smaller in the fourth trial compared with the first trial. This means that the operator's skill in this tracking task is improved by training. The transfer function gains $|H_{11}(j\omega)|$ and $|H_{22}(j\omega)|$ are almost zero [dB] and unchanged through the training. One possible reason is that the human operator can predict the required distance of the arm movement. As for the coupling motion, the phase curves of $H_{12}(j\omega)$ and $H_{21}(j\omega)$ imply the existence of time delay. Thus we know that the hand coupling motion has a characteristic of time delay.

To evaluate the skill based on the frequency response identification results, a criterion function is defined to quantify the operator's skill. For an expert operator, the criterion function is zero. Table 1 shows the criterion function values in the first and the forth trials. Thus using the criterion function, we can measure the level of operator's skill.

Table 1

Evaluated criterion function values

	Subject A	Subject B	Subject C	Subject D
1st Trial	0.0059	1.0788	0.0200	0.0117
4th Trial	0.0026	0.4444	0.0044	0.0070

3. X-Y STAGES

Based on the operation conditions, such as the moving range, speed, and frequency for a normal operator, the XY-stages were designed with the size being 60 cm in both X and Y axes and with two DC motors, which can drive the stages with necessary torque and necessary speed [39].

3.1. MOTORS AND ENCODERS

As the arm moving along Y axis is mounted on the arm moving along X axis, the motor to drive the XY-stage along X axis is more powerful than the one used in Y axis. The DC motors used in X and Y axes are SGDS-08A01A and SGDS-04A01A of Yaskawa Electric Cooperation products, respectively. They can provide up to 19.3 N-m and 10.3 N-m output torque for X and Y axes, respective with 750 W and 400 W. Both encoders for X and Y axes are with 2048 P/Rev resolution.

a) X Axis   b) Y Axis   c) Force Sensor with Grip

Fig. 26 – Motors, encoders and force sensor used in X-Y stages.

3.2. FORCE SENSOR

A grip is mounted on a 6-dimension force sensor (Nitta, IFS-70M35A25-M50B). The nominal force ranges are 100 N along X and Y directions and 200 N along Z direction. The nominal moment ranges are 10 Nm about all three axes. The resolutions are 0.01 N in X and Y and 0.02 N in Z while they are 1 Nmm in all three moments.

3.3. X-Y STAGE CONTROL SYSTEM

The X-Y stages are controlled by a PID compensator based on the Virtual Internal Model control method [11]. The control block diagram is shown in Fig. 27. And the parameters of X-Y stage are shown in Table 2.

Fig. 27 – Controller of X-Y stage.

Table 2

Parameters of X-Y stage
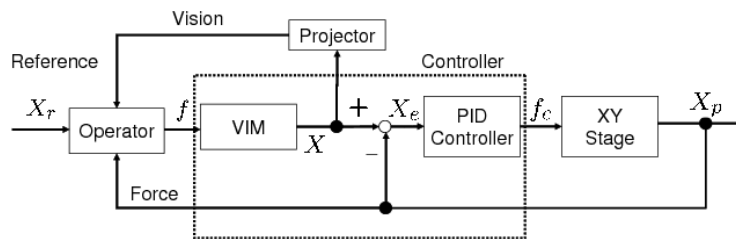
$F_h[\text{N}]$	Force by operator
$F_c[\text{N}]$	Control input
$M_{md}[\text{kg}]$	Mass of VIM
$D_{md}[\text{Ns/m}]$	Viscosity of VIM
$X_{md}[\text{m}]$	Position of VIM
X_p	Position of X-Y stage
$M_p[\text{kg}]$	Mass of X-Y stage
$D_p[\text{Ns/m}]$	Viscosity of X-Y stage
e_m	Error $X_{md} - X_p$

The model of the X-Y stage can be written as

$$M_p X_p + D_p X_p = F_h + F_c.$$

Therefore the virtual internal mode of the XY-stage used in the controller is determined by

$$M_m X_m + D_m X_m = F_h,$$

with parameters

$$M_p = 26 \text{ kg}, \ D_p = 22 \text{ Ns/m}, \ M_m = 7 \text{ kg}, \ D_m = 10 \text{ Ns/m}.$$

The PID compensator is in the form of

$$F_c = M_m^{-1}(M_p(-D_m X_m + F_h) \ \ + D_p X_p - F_h - FEM_p$$

where $F = \begin{bmatrix} K_I & K_P & K_D \end{bmatrix}$, $E = \begin{bmatrix} \int e_{mx} \mathrm{d}t \\ e_{mx} \\ \dot{e}_{mx} \end{bmatrix}$, and $\begin{array}{l} K_P = 0.000006 \\ K_I = 21232.0 \\ K_D = 65.135. \end{array}$

4. EXPERIMENT SETUPS

Three right-handed healthy male students as the subject with their age ranging from 21 to 27 participated in this research. None of them has special life background which may result in a high motor skill such as player of piano or violin

or sportsman. They were asked to stand in the front of X-Y stages in their most comfortable posture, look at the screen of a project connected to the PC which gives the reference trajectories for left and right hands and shows the real trajectory of the X-Y stages, move two X-Y stages with his left and right hands respectively as shown in Figs. 28 and 39 to track two reference trajectories given in the screen.

Fig. 28 – Experimental Scene 1.

Fig. 29 – Experimental Scene 2.

The trajectories to be tracked are rhythmic signals either alone a straight line or alone a circle. The frequency and the phase of each reference trajectory may be adjusted according to the experimental requirements.

4.1. EXPERIMENT 1

In this experiment, the spatial coupling is investigated when the subjects are asked to move the XY-stages to track two trajectories running on a straight line and a circle, respectively. The experimental environment is shown in Fig. 30.

On the right side of the screen used to give the target commands to the human operator, there are a circle, a point on the circle, and a symbol "x". The point moves on the circle with a fixed radius in a certain speed. The symbol "x" shows the current position of the left X-Y stage. On the left side of the screen, there are a straight line, a point on the line, and a symbol "x". The point moves on the line with a certain speed. The symbol "x" shows the current position of the right X-Y stage. The operators are asked to hand the grips mounted on the force sensors and to move the X-Y stages through the grips so that the positions of the X-Y stages track the points running on the line and the circle, respectively. The forces from the operators' hands and the positions of the X-Y stages are recorded for the analysis of the experimental results. The moving speeds of the point on the line and the circle are changed with the frequency being $\omega = 0.3$, 0.4, 0.5, 0.7, 1.0 Hz. The trajectories of reference points denoted as ($x_{left}(t)$, $y_{left}(t)$) and ($x_{right}(t)$, $y_{right}(t)$) are determined by

$$x_{left}(t) = 0$$

$$y_{left}(t) = \frac{r\pi}{2\omega} \int_o^t \text{sign}(\cos(\omega t)) \mathrm{d}t$$

$$x_{right}(t) = r\cos(\omega t)$$

$$y_{right}(t) = r\sin(\omega t)$$

where $r = 0.05\,\text{m}$ and ω changes with

$$\omega = 0.3, 0.4, 0.5, 0.7, 1.0\,\text{Hz},$$

and the frequency ratio f takes values among

$$f = 1/1, 2/1, 4/3, 5/3, 6/5.$$

4.2. EXPERIMENT 2

In this experiment, the effect of the frequency ratio on the operators' operation skill is investigated when the subjects are asked to move the XY-stages to track two trajectories moving on circles, respectively. The experimental environment is shown in Fig. 31.
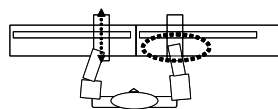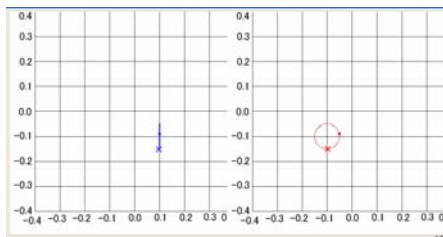

Fig. 30 – Environment of Experiment 1.   Fig. 31 – Environment of Experiments 2&3.

On the screen, there are two circles, a point on each circle, and two symbol "x"'. The points move on the circles with a fixed radius in a certain speed. The symbol "x" shows the current positions of the left and right X-Y stages. The moving speed of the point on the left circle are changed with the frequency being $\omega = 0.3$, 0.4, 0.5, 0.7, 1.0 Hz and the frequency ratio between two trajectories

are set to be $1:1$, $1:2$, $3:4$, $3:5$, and $5:6$. The trajectories of reference points denoted as ($x_{left}(t)$, $y_{left}(t)$) and ($x_{right}(t)$, $y_{right}(t)$) are determined by

$$x_{left}(t) = r\cos(\omega t)$$
$$y_{left}(t) = r\sin(\omega t)$$
$$x_{right}(t) = r\cos(f\omega t)$$
$$y_{right}(t) = r\sin(f\omega t)$$

where $r = 0.05\,\text{m}$ and ω changes with
$$\omega = 0.3, 0.4, 0.5, 0.7, 1.0\,\text{Hz}$$

and the frequency ratio f takes values among

$$f = 1/1, 2/1, 3/4, 3/5, 5/6.$$

4.3. EXPERIMENT 3

In this experiment, the experimental setup is similar to the one in Experiment 2 except that the frequency ratio is fixed to be $1:1$ but the phase-lag between two trajectories for the left and the right hands are considered to be 0 degree, 45 degree, 75 degree, 90 degree, 125 degree, and 180 degree. The trajectories of reference points denoted as ($x_{left}(t)$, $y_{left}(t)$) and ($x_{right}(t)$, $y_{right}(t)$) are determined by

$$x_{left}(t) = r\cos(\omega t)$$
$$y_{left}(t) = r\sin(\omega t)$$
$$x_{right}(t) = r\cos(\omega t + \theta)$$
$$y_{right}(t) = r\sin(\omega t + \theta)$$

where
$$r = 0.05\,\text{m}$$
and ω changes with
$$\omega = 0.3, 0.4, 0.5, 0.7, 1.0\ \text{Hz},$$

and the phase-lag θ takes values among

$$\theta = 0, 45, 75, 90, 125, 180\ \text{deg}.$$

5. EXPERIMENTAL RESULTS AND DISCUSSES

5.1. SPATIAL COUPLING

As the results of Experiment 1, Fig. 32 shows the spatial coupling existing in bimanual operation when two trajectories on a straight line and on a circle are tracked by two X-Y stages, respectively. And the coupling becomes stronger for a higher moving speed of X-Y stages.

(0.2 Hz)

(0.3 Hz)

(0.7 Hz)

Fig. 32 – Line and circle tracking result.

5.2. EFFECT OF FREQUENCY RATIO

Figure 33 shows the tracking error for each frequency ratio in Experiment 2. It is clear that the trajectories on circles are much more difficult to track and thus are with much larger tracking error when the number in nominator and/or denominator is larger.

(1:1)   (1:2)

(3:4)   (3:5)

(5:6)

Fig. 33 – Circle tracking error with different frequency ratio.

Figs. 34 and 35 show the development of the human operator's operation skill where the tracking performance is improved after the ope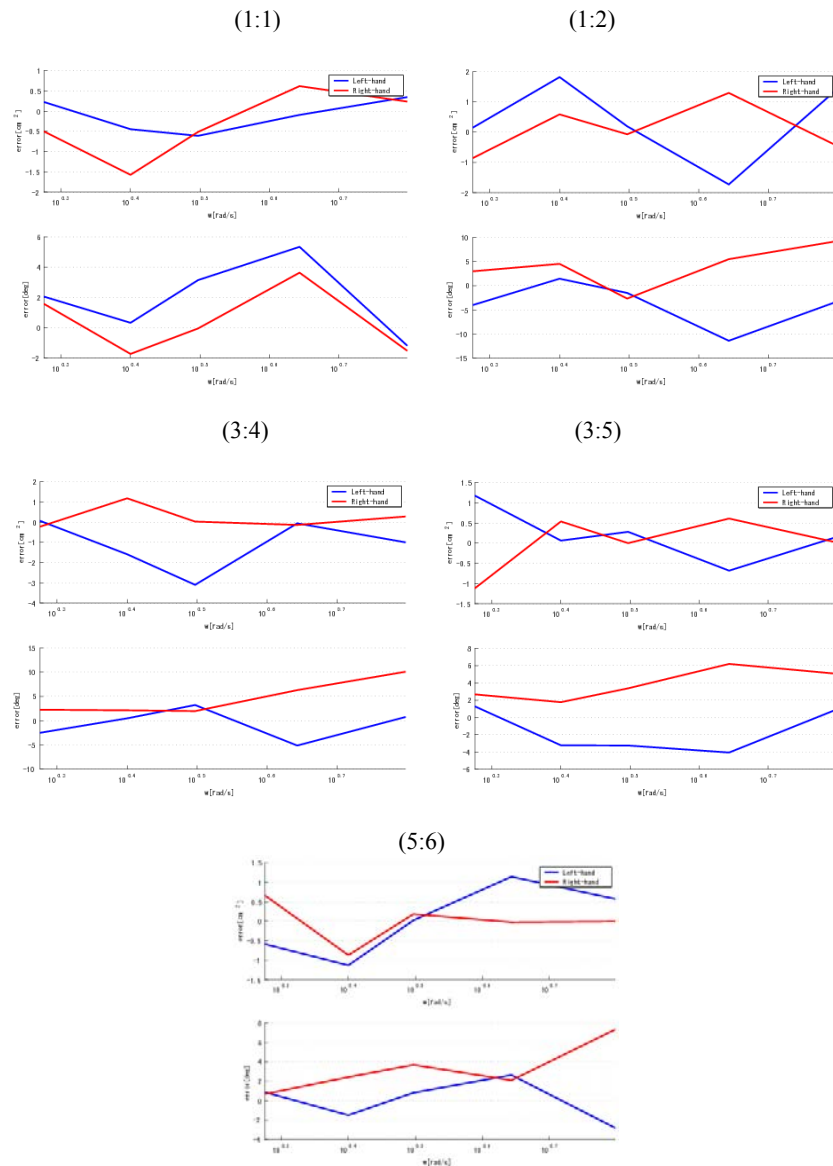rator repeated his operation several times. It is found that the skill is quit improved for low speed operation and is not improved for higher speed operation when the frequency ratio is with larger numbers in its nominator and/or denominator. When the X-Y stages are operated in the same frequency and the same phase, the operation skill is improved in both low and high speed operation.

(1st Try)   (2nt Try)

(3rd Try)   (4th Try)

Fig. 34 – Skill development in circle tracking (1:1).

(1st Try)   (2nt Try)

(3rd Try)   (4th Try)

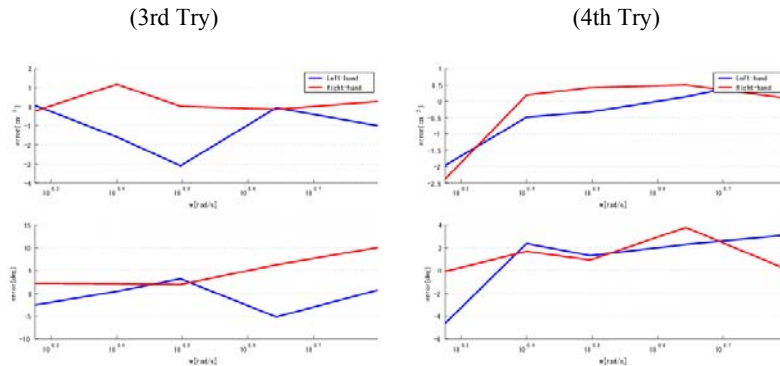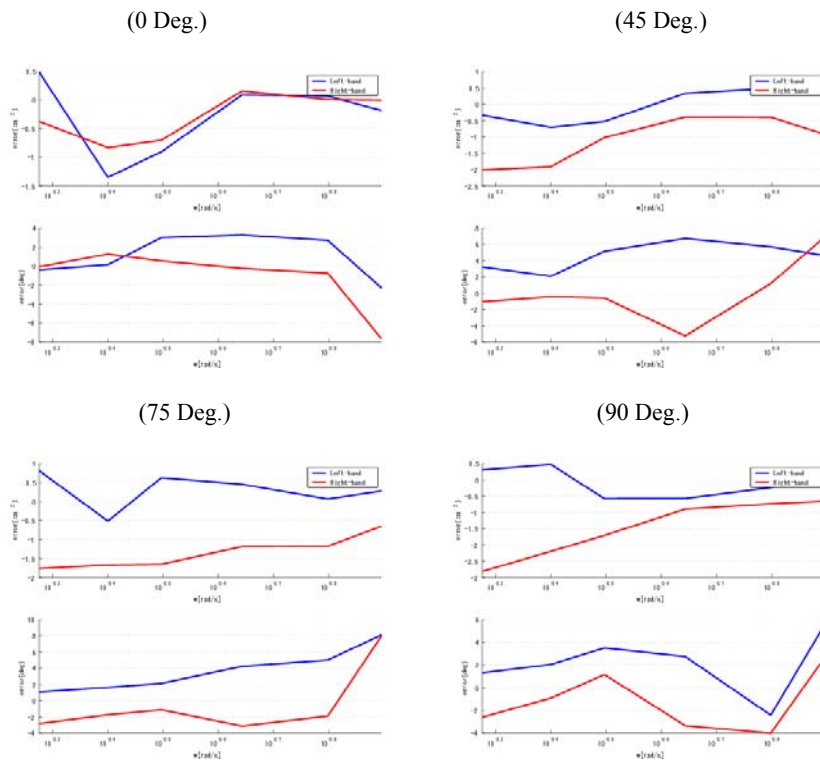Fig. 35 – Skill development in circle tracking (3:4).

5.3. EFFECT OF PHASE-LAG

The effect of the phase-lag was observed in Experiment 3 as shown in Fig. 36. It is found in the experiment that the skill is difficult to be improved when there exists phase-lag between two X-Y stages' operations.
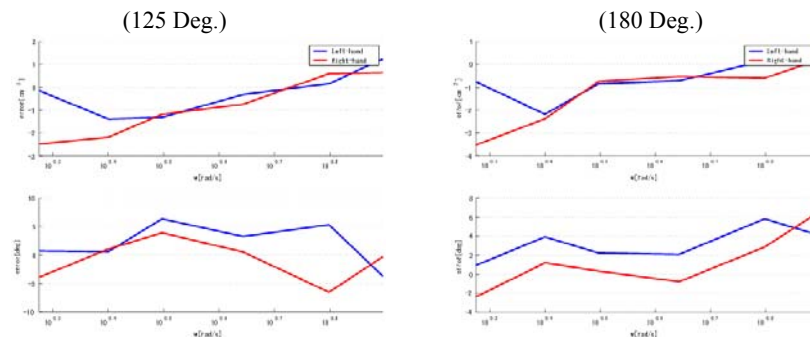
(0 Deg.)   (45 Deg.)

(75 Deg.)   (90 Deg.)

(125 Deg.)   (180 Deg.)

Fig. 36 – Circle tracking error with phase-lag.

6. CONCLUSION

In this paper, some HAM research results in TDU about operator skill evaluation, operation assistance, identification of operator's dynamics, skill acquisition, and coupling phenomenon in bimanual operation were presented. Then two X-Y stages were designed. The experimental results to investigate the phenomenon of spatial coupling, the effect of frequency ratio and phase-lag were given. It was found that the bimanual operation is much more difficult and the skill is difficult to be improved when the frequency ratio is with larger numbers in its nominator and/or denominator and/or there exists phase-lag except of anti-phase. Besides, some research results in TDU about operator skill evaluation, operation assistance, identification of operator's dynamics, skill acquisition, and coupling phenomenon in bimanual operation were presented.

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