Investigation on Force Scaling for Multi Degree of Freedom Bilateral Teleoperation Control System

Ahmad Zaki Shukor, Lee Jun Wei, Muhammad Herman Jamaluddin
Center of Excellence in Robotics and Automation (CeRIA),
Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM)

***Abstract*— A bilateral control system consists of two actuation systems which are separate but sends and receives information to and from each other. Information shared consists of calculated force and position readings from sensors which feed into the control system. When the actuation systems are in the form of robot manipulators, there are at least two degrees of freedom with each degree of freedom has its own force and position values. When these two systems operate simultaneously, a change in force and position for one system triggers the other to coordinate and attempt to maintain the same values of force and position at both sides and this is termed as a master-slave system. In most cases, both systems are identical and the amount of force and position desired is similar. In some real-life applications, the desired amount of force/position is scaled; i.e. smaller or larger force is desired at one end of the system (master/slave). For this purpose, this research proposes a method to scale the force at either master or slave side by using elements of the mass/inertia matrix of the robot manipulator. Four different scaling values were demonstrated in the experiments to show the validity of the proposed method. Results indicate that the method is viable as the forces were scaled correctly as desired.**

***Index Term*— micro-macro, standardization, modal space, haptics, MDOF bilateral teleoperation control system, geared DC-motor.**

I. INTRODUCTION

REMOTE control operations of autonomous systems have now become favorable due to wireless connectivity and speed of communications [1]. Aerial robots, robot boats and ground mobile robots are often used for navigating or investigation terrains for the purpose of acquiring information or manipulating objects [2], military surveillance/tracking [3] or even perform rescue operations [4]. Such application of robots was seen in the Fukushima earthquake disaster [5]. A mobile robot with an arm manipulator was deployed to navigate in the dangerous radioactive environment. It is not desired to risk a human life in such an environment. For navigation in an environment, information such as image, videos of the environment is the usual data acquired but in some cases, it is important to interact with the environment. The information from the environment is usually sent to the server unilaterally, i.e. the robot does not receive this information back from the server. In the case of interaction, the remote control/operator needs to feel the information from the environment and send the reaction back to the robot. A rescue operation robot should not stumble upon a human casualty and injure him/her while navigating in the environment. This kind of interaction requires the information to be in a two-way mode, or bilateral communication.

Another example of an environment which requires this kind of information is the remote surgery. A surgeon is placed in a different location than the patient who is undergoing surgery. The surgeon manipulates the apparatus in his/her space and which will actuate the apparatus at the patient's location. Other than the image sent from the camera at the location of the patient for the purpose of moving the apparatus accordingly, the surgeon requires the sensation of force from the patient's side. This is needed because the surgeon will control the force he/she applies to the patients organs. Giving excessive or insufficient force might fail the operation and result is severe complications or death to the patient. This kind of delicate operation (in the field of haptics) is called micro-macro bilateral teleoperation control system. The micro-macro bilateral teleoperation control system consists of macro (large) master system and micro (small) slave system. To manipulate micro object (surgical apparatus), the slave system (at the patient side) is generally smaller compared to master system (at the surgeon side). This is where the scaling technique is used for force and position between master and slave manipulator which is different in size. A large force by the surgeon should be scaled down to suit the force in the operation room. This method enables human operator to manipulate the master and slave system with a different-sized structure. The micro-macro bilateral teleoperation control system provides the human operator with a sense of feel to a micro or macro environment as if it is in the same environment. In other words, the human operator feels the reaction force as if touching the real micro or macro environment. This bilateral force feedback is indeed useful in recent advances in surgery, for example minimally invasive surgery only operates on small incisions instead of large opening [6][7].

Force scaling could also be done for small to large actuation systems. An example of this kind of application is tele-operated excavators reviewed in [8][9]. In cases where the environment is dangerous to human, such tele-operated excavator proves to be a viable option to remove debris in post-disaster recovery work. Disasters such as volcanic eruptions that rendered an island in Japan uninhabitable, as experienced by the Japanese in 1994 Mount Fugen and Mount Usuzan in 2000 showcased the use of wireless remote tele-operated unmanned system. Earthquakes and also tsunami post-disaster recovery works also witnessed the use of remote-controlled hydraulic excavators, as in the latest 2011 Fukushima earthquake-tsunami. In Malaysia, Yusof et al [10] developed a specific tele-operated electrohydraulic actuator for construction works using mini excavator which operates on 2.4 GHz radio-controlled transmission system. The actuation uses a tie-rod cylinder coupled with 24V DC electro-hydraulic valve.

Force and position scaling for bilateral teleoperation system was investigated by some researchers, but on single degree of freedom actuators. One side of the system (master/slave) is smaller physically than the other. Control methods for this setup were investigated by K. Kaneko. The researcher presented operational force feedforward for micro-macro bilateral teleoperation control system [8]. Before that, K. Takeo proposed an alternative control algorithm for micro-macro teleoperation system [9]. Another researcher, A. Sano used scaling factors based on H_∞ theory and proposed stabilization method on bilateral teleoperation control system [10]. Then Shimono proposed the standardization between master response and slave response by nominal mass of master and slave system in micro-macro bilateral teleoperation control was proposed [11][12]. S. Susa presented scaling factors of the control gains at master and slave system in the micro-macro bilateral teleoperation control system [13]. S. Susa further presented with three channel micro-macro bilateral teleoperation control with arbitrary scaling factors able to achieve high accuracy control although with less information channels [14]. N. Motoi proposed a modal space disturbance observer (MSDOB) in the micro-macro bilateral teleoperation control system to realize high transparency [15].

The related researches on force and position scaling ([8] to [15]) that were done deals with one degree of freedom actuation. This means that there is no issue of complexity since the one degree of freedom on the master side can be directly linked to the slave without any need to convert coordinates or sophisticated modeling. In most actual physical systems, the end effector or tool point is moved by the operator to sense/feel the environment, and in the case of robot manipulators, the number of degree of freedom for each end effector motion will depend on the number of actuation or joints involved. For robot manipulators, it is usually 2 or more degrees of freedom. Hence, we propose the force scaling of multi degree of freedom bilateral system using standardized modal space. In this paper, the scaling is done in terms of torque. But as a general understanding, the same concept can be applied to force.

This paper is organized as follows; Section II introduces the bilateral teleoperation control system. Section III explains the control method using disturbance observer (DOB) and reaction torque observer (RTOB). Section IV explains the two degree of freedom bilateral control system. Next, Section V explains on multi degree of freedom force scaling control system. Section VI shows the experimental setup of the two degree of freedom bilateral teleoperation control system. Section VII discusses the experimental results and Section VIII concludes the outcome of the research.

II. Bilateral Teleoperation Control System

Newton’s law of action and reaction is a well-known proven theory. The law of action-reaction (Newton's third law) explains the nature of the forces between the two interacting objects. According to the law, the force exerted by object 1 upon object 2 is equal in magnitude and opposite in direction to the force exerted by object 2 upon object 1.

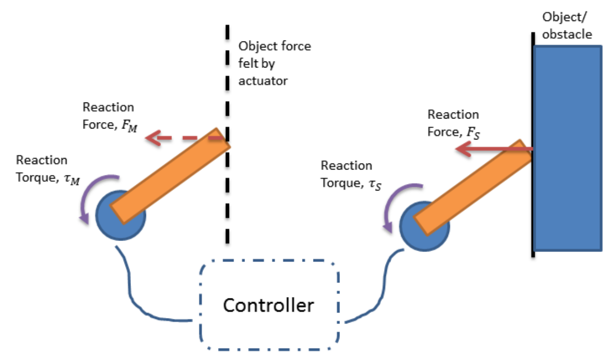

Fig. 1. Illustration of Bilateral Teleoperation System

The law of action and reaction is easily visualized when the two objects exists in the same workspace. However for remote operations, one object is represented by two systems separately, which are the master and slave systems, as seen in Figure 1.0. The object/obstacle/environment that it is reacting to exists in only one of the two systems. But the reaction felt from the system that interacts with the actual environment is also transferred to the other system. In other words, the environment virtually exists in the other system. In this case, the force/sensation is transmitted bidirectional or bilaterally, hence the name bilateral teleoperation. If the actuation is rotational, the relation between the torque at the master and slave side can be related by Equation (2.1);

$$\tau_M + \tau_S = 0 \qquad (2.1)$$

where subscript M and S denote the master and slave system accordingly. The summation of torques at each side will always result to zero. Any reaction on master or slave side will cause the other system to feel the same because of this bilateral force/torque relation. The torque regulation is called common mode. However, the position (angle) values for both master and slave system should be in negative magnitude than the other. In other words, the position error between master and slave system should be equated as in (2.2);

$$\theta_M - \theta_S = 0 \qquad (2.2)$$

It can be seen that the bilateral system has to maintain the law of action and reaction and at the same time regulate the position error to zero. Position regulation is called differential mode. Although the theory is simple, actual realization of this bilateral teleoperation system depends on the speed of communication and processing power of the controller for the system.

For the perception of force sensation, both torque and position displacement should be transferred bidirectional. The total block diagram of bilateral motion control is summarized in Figure 2.1 [20]. Table I shows the list of parameters' definitions of this paper.

TABLE I
LIST OF PARAMETER SYMBOLS

Parameter	Description
l_1	Link 1
J	Real inertia
J_n	Nominal inertia
J_m	Motor inertia
J_L	Load inertia
N	Gear ratio
K_{tn}	Nominal torque constant
K_p	Proportional gain
K_d	Derivative gain
K_f	Force gain
C_p	Position controller
C_f	Force controller
ω_n	Natural angular frequency
δ	Damping coefficient
g_{dob}	Cut-off frequency of disturbance observer
g_{rtob}	Cut-off frequency of reaction torque observer
τ	Torque
θ	Angle
$\dot{\theta}$	Angular velocity
$\ddot{\theta}$	Angular acceleration

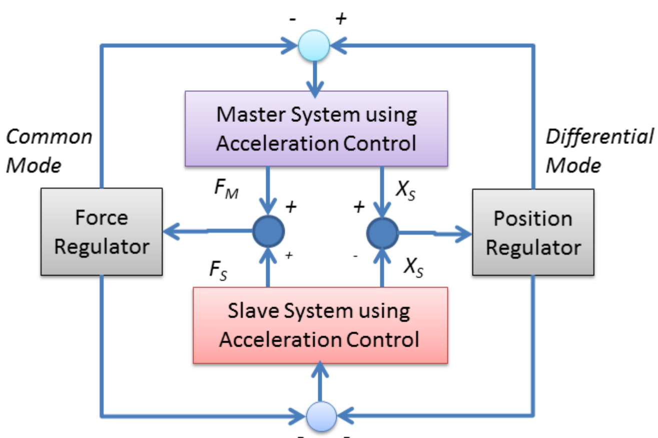

Fig. 2.1. General block diagram of bilateral motion control by acceleration control

For ensuring continuous bilateral motion control, the total force in common mode, τ_C and the total acceleration in differential mode, x_D has to be maintained [20]. Note that the common mode and differential mode are independent of each other. For interaction between these two modes, the Hadamard matrix (Quarry matrix), H_2 is used for modal decomposition, as seen in Equation (2.7). Equations (2.3) to (2.7) show the characteristics of the second order Hadamard matrix.

$$\ddot{\theta}_M^{ref} = -C_p\theta_D^{res} + C_f F_C^{res} \quad (2.3)$$

$$\ddot{\theta}_S^{ref} = C_p\theta_D^{res} + C_f F_C^{res} \quad (2.4)$$

$$\theta_D^{res} = (\theta_M^{res} - \theta_S^{res}) \quad (2.5)$$

$$\tau_C^{res} = (\hat{\tau}_M^{ext} + \hat{\tau}_S^{ext}) \quad (2.6)$$

$$\begin{bmatrix} \tau_C^{res} & \theta_D^{res} \\ \tau_C^{res} & \theta_D^{res} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \hat{\tau}_M^{ext} & \theta_M^{res} \\ \hat{\tau}_S^{ext} & \theta_S^{res} \end{bmatrix} = H_2 \begin{bmatrix} \hat{\tau}_M^{ext} & \theta_M^{res} \\ \hat{\tau}_S^{ext} & \theta_S^{res} \end{bmatrix} \quad (2.7)$$

In Equations (2.3) to (2.6), superscript '*res*' denotes response, superscript '*ext*' means external while subscript '*S*' and '*M*' indicates slave and master systems. Equation (2.3) and (2.4) maintains the acceleration of the master and slave using force information and position control. The position controller C_p and the force controller C_f are used. Equation (2.5) and (2.6) relates to the regulation of position error in critical damped response and maintaining the law of action and reaction.

Force information could be obtained in different ways. While most of researches use actual force sensors to retrieve force information, this bilateral control system could use the disturbance observer (DOB) [21] and the reaction torque observer (RTOB) [22] to determine the force disturbance and external forces that exist in both the master and slave systems. Disturbance estimation is explained in the following section. This disturbance estimation provides robust control of the system. Fig. 2.2 describes the detailed block diagram of single link bilateral control based on acceleration control.

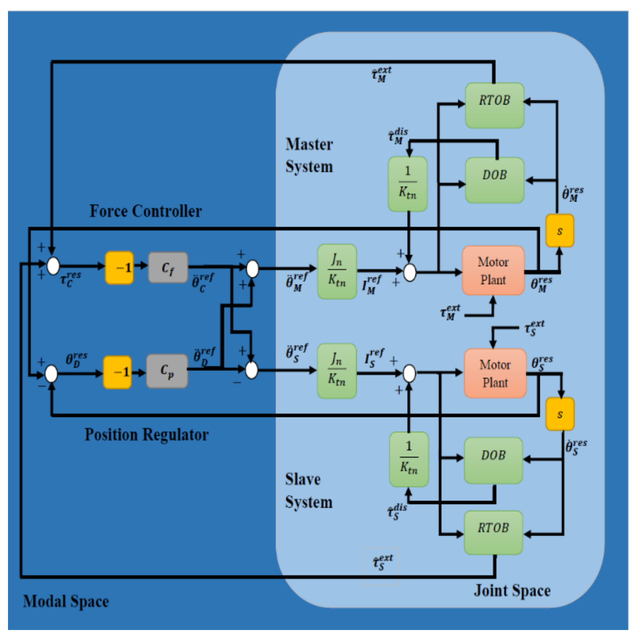

Fig. 2.2. Detailed block diagram of single link (joint actuation) bilateral control based on acceleration control

The position and velocity coefficients are set based on the natural angular frequency and a damping coefficient of the control system as shown in Equation (2.8) and Equation (2.9)

[23]. The force controller system has to maintain the contact stability between force at end-effectors and the force at the contact object. It is defined as;

$$K_p = \omega_n^2 \quad (2.8)$$

$$K_d = 2\delta\omega_n \quad (2.9)$$

$$C_p = K_p + K_d s \quad (2.10)$$

$$C_f = K_f \quad (2.11)$$

Since the system uses single rotational actuators (motor) for both master and slave side, the nominal inertia, J_n of the master and slave system is similar. The shaft at the end of the gearhead is attached with the coupling and a link. Thus the total nominal inertia is calculated as;

$$J_n = J_m + J_L(\frac{N_1}{N_2}) \quad (2.12)$$

Where J_m represents the motor inertia, J_L represents the load inertia, and N_1 and N_2 are gear ratios of the motors respectively.

III. Control Using Disturbance Observer (DOB) and Reaction Torque Observer (RTOB)

While some researchers use high cost force sensors to perceive the force from the end effector used, a method to estimate the force provides a robust solution. Disturbance observers estimate not only the external disturbance, but also system uncertainties. With the disturbance estimation fed back to the control loop, this method will cancel or compensate the disturbance instantly. The control system becomes a robust acceleration control system [24]. The friction under the constant angular velocity motion in the mechanism becomes the output of the DOB in steady state. A robust system means that the system is insensitive to the external disturbance and parameter variations and can compensate them immediately. It can obtain wider bandwidth than force sensors due to setting sampling time and observer gain by using DOB technique [22]. The feedback of estimated disturbance in the inner-loop is to obtain the robustness of the motion control system [25]. On the contrary, the outer-loop estimates the external forces or disturbance to realize force regulation. In the outer loop, the PD controller is designed in order to fulfil performance requirements of the motion control system [25]. Both outer and inner loop are related to maintain robustness.

The block diagram of joint space actuation based disturbance observer and reaction torque observer is shown in Fig. 3.1. This arrangement of control compensates the disturbance effect within the motor plant and estimate the external torque from both the master and slave manipulators, respectively.

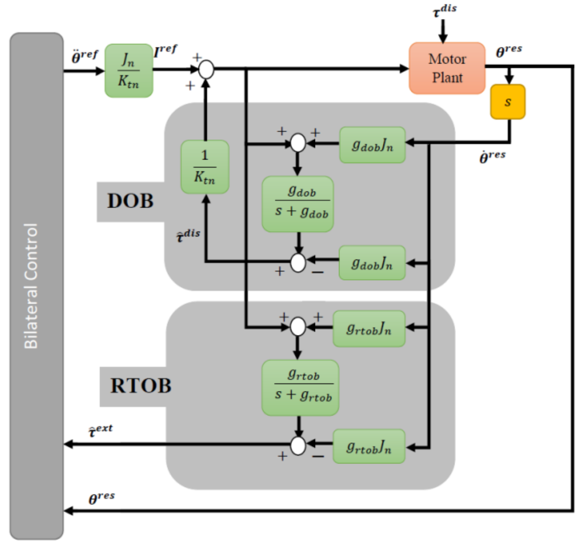

Fig. 3.1. Joint space actuation based disturbance observer and reaction torque observer

$$\tau_{dis} = (J - J_n)\ddot{\theta}^{res} + (K_{tn} - K_t)I^{ref} + F_c + D\dot{\theta}^{res} + \tau^{ext} \quad (3.1)$$

$$= \Delta J\ddot{\theta}^{res} - \Delta K_t I^{ref} + \tau_l \quad (3.2)$$

$$\Delta J = J - J_n \quad (3.3)$$

$$\Delta K = K_t - K_{tn} \quad (3.4)$$

$$\tau_l = F_c + D\dot{\theta}^{res} + \tau^{ext} \quad (3.5)$$

where;

F_c	Coulomb friction;
$D\dot{\theta}^{res}$	Viscous friction;
ΔJ	Self-inertia variation;
ΔK	Variation of torque coefficient;
τ_l	Load torque;

In Equation (3.1), the first term and second term are the torque pulsations due to self-inertia variation and variation of the torque coefficient of the motor, respectively. The Coulomb and the viscous friction respectively are denoted in the third and fourth term. The last term, τ^{ext} is the reaction torque caused by external torque.

The disturbance torque is estimated from the current reference and velocity response. The estimated torque, $\hat{\tau}^{dis}$ is estimated using Equation (3.6)

$$\hat{\tau}^{dis} = \frac{g_{dob}}{s + g_{dob}}\tau^{dis} \quad (3.6)$$

where;

$$\frac{g_{dob}}{s + g_{dob}} \quad (3.7)$$

is the DOB low-pass filter (LPF) and g_{dob} is the cut-off frequency.

$$\hat{\tau}^{dis} = \frac{g_{dob}}{s + g_{dob}} \left(g_{dob} J_n \dot{\theta}^{res} + I^{ref} \right) - g_{dob} J_n \dot{\theta}^{res} \quad (3.8)$$

Realization of robust motion control is attained by using Equation (3.6). The bandwidth of the DOB low-pass filter as in Equation (3.7) is set as high as possible to estimate a wide frequency range of disturbance. However, limitations in hardware and processing time will result in limitation in the highest value that can be set.

In addition, by subtracting the external disturbances and system uncertainties from input of a DOB, it can estimate the reaction torque applied to the system. It is necessary and important to identify them as precisely as possible. This process is called as Reaction Torque Observer (RTOB) [22] as shown is Fig. 3.1. Equation (3.9) shows that the reaction torque observer is estimated through first-order Low Pass Filter (LPF). RTOB can estimate external torque/force without torque/force sensor. For force, the same concept is applied and is called Reaction Force Observer (RFOB). The study of comparison between force sensor and reaction force observer based on force control system has been detailed in [26].

$$\hat{\tau}^{ext} = \frac{g_{rtob}}{s + g_{rtob}} \tau^{rext} \quad (3.9)$$

where

$$\frac{g_{rtob}}{s + g_{rtob}} \quad (3.10)$$

is the DOB low-pass filter (LPF) and g_{rtob} is a cut-off frequency.

The experimental validation of single degree of freedom bilateral teleoperation system using rotational actuator (motor) was shown in [27]. The findings show effect of the variation of parameters (controller and disturbance observer gains) on the force and position responses.

IV. Two Degree Of Freedom Bilateral Teleoperation System

A robot manipulator configuration usually has more than one actuator for flexibility of manipulation. For articulated robots, most industrial robot manipulators are six degrees of freedom. This is to ensure that the Jacobian matrix that links the Cartesian and joint space is square and invertible. Thus this type of manipulator is a multi-degree of freedom system. However, in this paper, we will investigate only two degrees of freedom for ease of application. An n-dof manipulator will depend on its dynamic modelling and control for force and position regulation for the purpose of bilateral teleoperation system.

For control of a robot manipulator, most applications are interested in the end effector position or force regulation. This is because the tool and workpiece must coincide for successful manipulation. The concept of workspace (end effector) control and different position control approaches was explained in [19]. Three different methods of control were presented, the first approach used Inverse Kinematics and then Proportional Derivative (PD) control of each joint independently, Direct Cartesian and Workspace PD control and finally Direct Cartesian and Disturbance Observer Control. It was shown that workspace control with Disturbance Observers, Workspace Observer (WOB) produced better results due to the estimation of the disturbance that is compensated in the control. An example of workspace observer (WOB) in the control loop is shown in Figure 4.1.

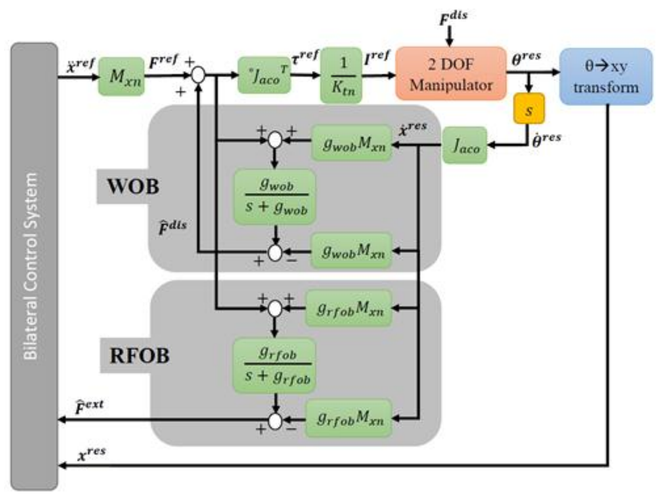

Fig. 4.1. Workspace Control of Bilateral Teleoperation System

To implement the bilateral teleoperation control system in two degrees of freedom, the same concept of law of action and reaction using Hadamard matrix is applied. However, the disturbance estimated is the end effector disturbance force in Cartesian coordinates (Workspace Observer) and end effector reaction force with the environment (RFOB), and not reaction torques in the single degree of freedom bilateral system. The bilateral teleoperation system which includes both master and slave system and the Hadamard matrix is shown in Figure 4.2.

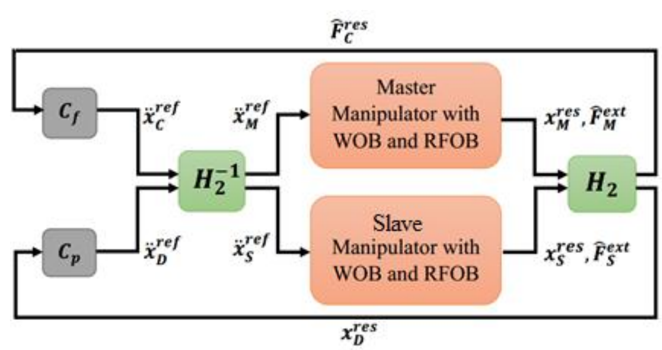

Fig. 4.2. Master and Slave Two Degree of Freedom Bilateral Teleoperation System using Hadamard Matrix

V. Force Scaling Of Multi Degree Of Freedom Control System

In Multi Degree of Freedom (MDOF) bilateral system with different structure, the operational range and mass between master and slave system are different. For instances, both system can have completely same motion but different operational range. Similarly, the force is reproduced much more than the other one if one system is much bigger than the other. Thus, the position and force between both systems need to be standardized by scaling second order quarry matrix shown in Equation (4.1).

$$H_2 = \begin{bmatrix} 1 & \alpha \\ 1 & -\beta \end{bmatrix} \tag{4.1}$$

where α is the scaling ratio of force information and β is the scaling ratio of position information. Thus, the slave system reproduces force and track position based on α and β gain with respect to master system. This proposed method is called as standardized modal space. However, by using this proposed method, α gain scaling scales force information with user-defined ratio. Micro-macro bilateral control system can reproduce lower or higher force output at the slave system according to the scaling ratio of nominal mass between the master and slave system with α gain, regardless of the mass of the slave system. This is able to produce the force information at slave manipulator according to the human operator arbitrarily. However, as a constraint, the actuator must be able to provide such amount of force.

Nevertheless, the force and position information are designed independently as using the Hadamard second-order matrix. Thus the length ratio between master and slave manipulator are designed accordingly to the structure of the master and slave manipulator with β gain, to obtain the correct position tracking, regardless of the mass of master and slave manipulator. Equation (4.2) shows the common mode force response and the differential mode position response obtained using the proposed method.

$$\begin{bmatrix} F_C^{res} & * \\ * & x_D^{res} \end{bmatrix} = \begin{bmatrix} 1 & \alpha \\ 1 & -\beta \end{bmatrix} \begin{bmatrix} \hat{F}_M^{ext} & x_M^{res} \\ \hat{F}_S^{ext} & x_S^{res} \end{bmatrix} = H_2 \begin{bmatrix} \hat{F}_M^{ext} & x_M^{res} \\ \hat{F}_S^{ext} & x_S^{res} \end{bmatrix} \tag{4.2}$$

Force information is scaled by the equivalent nominal mass matrix M_{xxn} and M_{yyn} in each system. The force scaling ratio, α_x and α_y are designed to scale force at each axis of $\hat{F}_S^{ext}$ of x-axis and y-axis as shown in Equation (4.3) and Equation (4.4), respectively.

$$\alpha_x = \frac{M_{xxMn}}{M_{xxSn}} \tag{4.3}$$

$$\alpha_y = \frac{M_{yyMn}}{M_{yySn}} \tag{4.4}$$

Position information is scaled by the operable region of each system by l_1 and l_2. The position scaling ratio, β is designed by utilizing l_1 and l_2 as in Equation (4.5).

$$\beta = \frac{l_{M1}}{l_{S1}} = \frac{l_{M2}}{l_{S2}} \tag{4.5}$$

Figure 3.38 shows the proposed four channel micro-macro bilateral control system with respect to the standardized modal space.

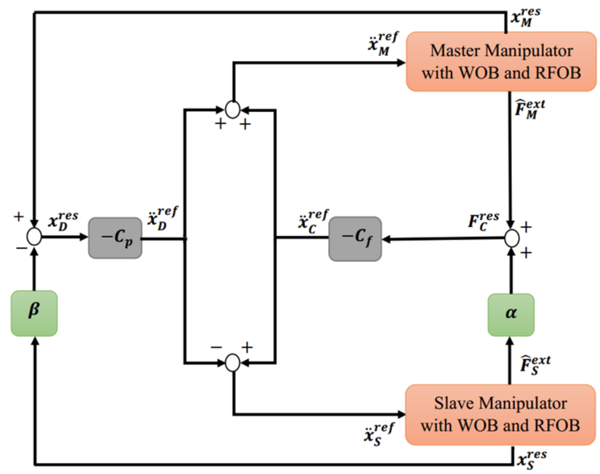

Fig. 5.1. Scaling of Multi Degree of Freedom Bilateral Teleoperation Control System

VI. Experimental Setup of Multi Degree Of Freedom Bilateral Teleoperation Control System

There are two sets of two link manipulators. The links are designed with a 0.12m each with a base attached to a platform to prevent any unwanted vibration. The link can be either used to operate the system by human operator on master side or to the environmental contact on the slave side. The arrangement of the links at both master and slave side are in horizontal orientation and thus will not produce any gravitational forces (no gravity force affects motion). The controller hardware used for the experiments is the Micro-Box 2000 x86-based Real-Time System. It is an affordable and robust platform for rapid control prototyping applications. It is rugged, high performance and can fulfil real-time analysis and control system testing needs. The control system for these experiments is designed using Simulink which is integrated to the Micro-Box and allow real-time modeling and simulation of control systems which is important to obtain real time data. Moreover, the sampling time of this Micro-Box can go up to 1ms. The DC motors used are Faulhaber DC Micromotors Series 3683 CR and its drivers are MAXON ESCON 50/5. The encoders of the motors are SCANCON 2RMHF of around 7500 pulse per revolution (PPR).

Two types of motion are performed in the experiments which are free and contact motion. During the free motion, the human operator control freely at master manipulator while the slave manipulator follows freely without contacting any object at the slave manipulator. While during the contact motion, the human operator operates the master manipulator manually and at this time the slave manipulator contacts the object. During contact motion, human operator holds the master handle and moves the handle while the slave handle is constrained by a static hard object. The human operator then applies extra force at the master handle. This extra force will try to push the static object and reaction force on the slave side will be induced and felt by the master side. The material of the experimental hard object is Aluminum. The experiment is as shown in Figure 6.1. Particularly, the human operator applied force on y-axis at the end-effector of master manipulator during contact motion as shown in Figure 6.2.

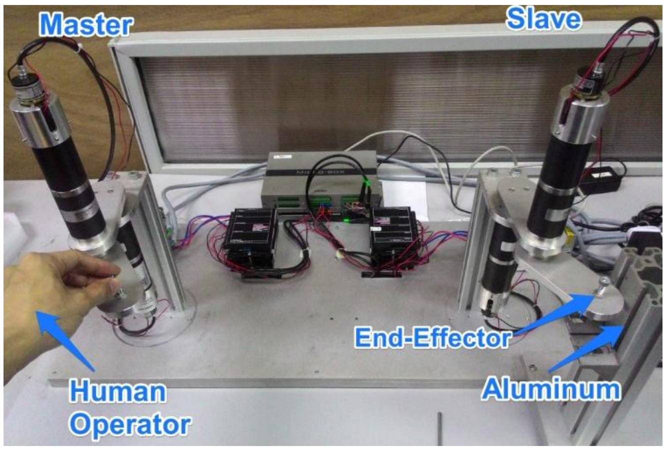

Fig. 6.1. Experimental setup for Master and Slave Systems

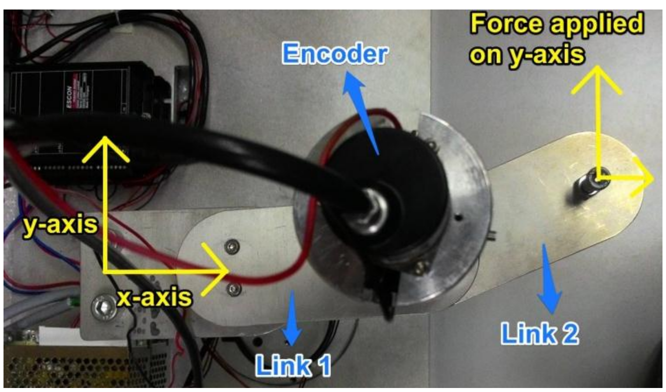

Fig. 6.2. Direction of applied force at the end-effector of master manipulator (top view)

The force and position responses from both master and slave system are recorded, for both free motion and contact motion experiments. The position responses from master and slave system are obtained from rotary encoder while the external force applied to the master and slave systems are estimated by RFOB. Velocity is computed from position values and noise is filtered with Low Pass Filter. The force and position response from both master and slave system are compared with each other to validate the performance of common mode and differential mode of bilateral control teleoperation system. The basic concept of bilateral motion control system on both master and slave system are required to comply in its total force in common mode F_C and total position in differential mode x_D according to Equation (3.62) and Equation (3.64), respectively. The common mode is the summation of force responses from both master and slave system while the differential mode is the differential of position responses from both master and slave system. Both common mode and differential mode must be zero in ideal condition.

Fig. 6.3. Micro-Box 2000 x86

VII. Experimental Results

For the free and contact motion experiment, there are 4 cases of scaling ratio to be conducted. Each case has different nominal mass ratio between master and slave system, M_{Mn}/M_{Sn}. The slave nominal mass M_{Sn} is set to two, three, four and five times heavier than the master nominal mass M_{Mn} while the actual nominal mass of the slave system remain the same. Then M_{xxn} and M_{yyn} are different between master and slave system according to each case. This ratio leaded to 4 cases of scaling in α gain too. Thus, the force response at slave also scaled according to α gain. The 4 cases of different nominal mass ratio between master and slave system are shown in Table II.

TABLE II
RATIO OF NOMINAL MASS AND LENGTH OF THE LINK BETWEEN MASTER AND SLAVE SYSTEM

Case	M_{Mn}/M_{Sn}	l_M/l_S
1	1/2	1/2
2	1/3	1/2
3	1/4	1/2
4	1/5	1/2

A. *Case 1*

The force for both x and y position tracked at slave system is twice larger than master manipulator as shown in Figure 7.1. This is due to the nominal mass at slave system is set twice larger than master system. If the force response of slave system is divided by two, then the performance of common mode is −0.0217N and 0.0395N for x-axis and y-axis, respectively. Overall, the law of action and reaction with scaling effect are achieved between master and slave system.

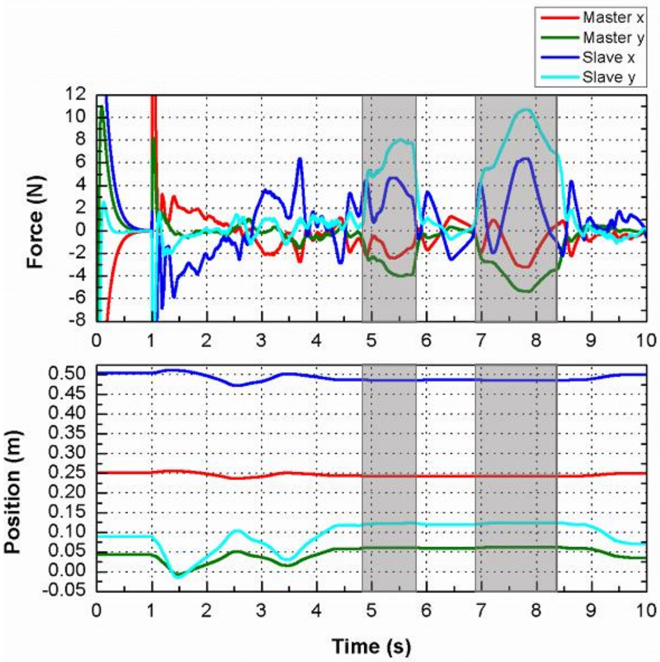

Fig. 7.1 : Force and position response during free and contact motion (Case 1)

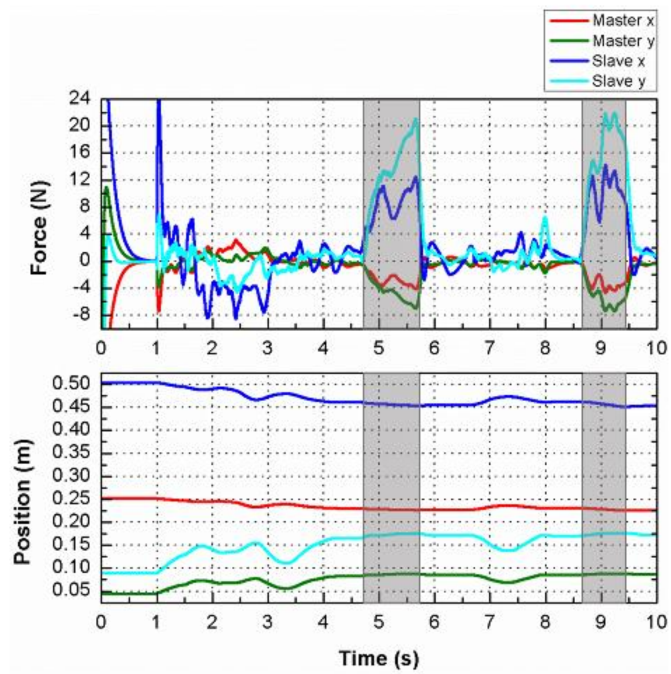

Fig. 7.2 : Force and position response during free and contact motion (Case 2)

Whereas, the and position response from slave manipulator are two times longer than the master manipulator for both and position as shown. This is because the length of each link of slave manipulator has virtually twice compared master manipulator. If the position response of slave system is divided by two, then the differential mode for x-axis and y-axis is -9.99×10^{-6}m and -2.97×10^{-6}m, respectively. Again, the position tracking from both master and slave system is tracked with almost zero mean error as the position response of both master and slave system are the same with scaling effect.

B. *Case 2*

The force for both x and y position tracked at slave system is twice larger than master manipulator as shown in Figure 7.2. This time the nominal mass at slave system is set three times larger than master system. If the force response of slave system is divided by three, then the performance of common mode is -0.0715N and 0.0528N for x-axis and y-axis, respectively. Again, the law of action and reaction with scaling effect are achieved between master and slave system.

Whereas, the x and y position response from slave manipulator are set two times longer than the master manipulator for both x and y position as shown. This is due to the length of each link of slave manipulator which is twice compared to master manipulator. If the position response of slave system is divided by two, then the differential mode for x-axis and y-axis is -2.98×10^{-6} m and -3.29×10^{-6}m, respectively. Again, the position tracking from both master and slave system are tracked with almost zero mean error as the position response of both master and slave system are the same with scaling effect.

C. *Case 3*

The force for both x and y position tracked at slave system is four times larger than master manipulator as shown in Figure 7.3. This is due to the nominal mass at slave system is set four times larger than master system. If the force response of slave system is divided by four, then the performance of common mode is -0.0472N and 0.0626N for x-axis and y-axis, respectively. Overall, the law of action and reaction with scaling effect are achieved between master and slave system.

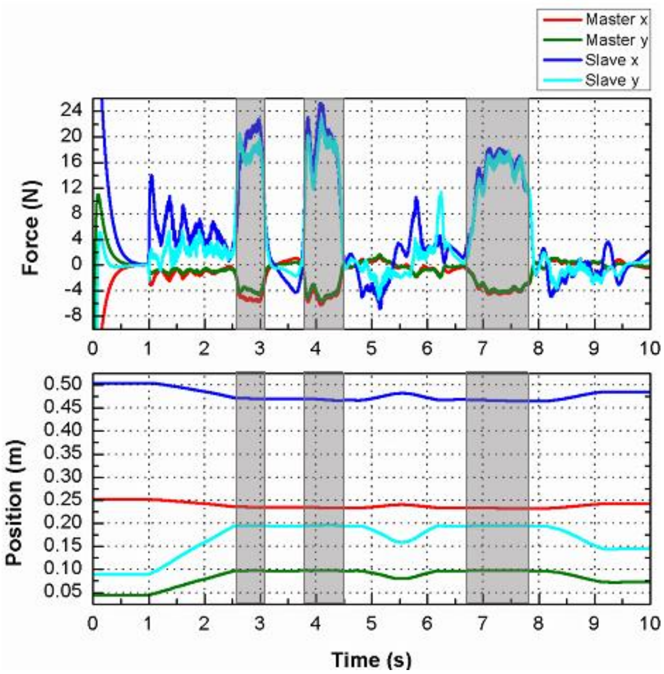

Fig. 7.3. Force and position response during free and contact motion (Case 3)

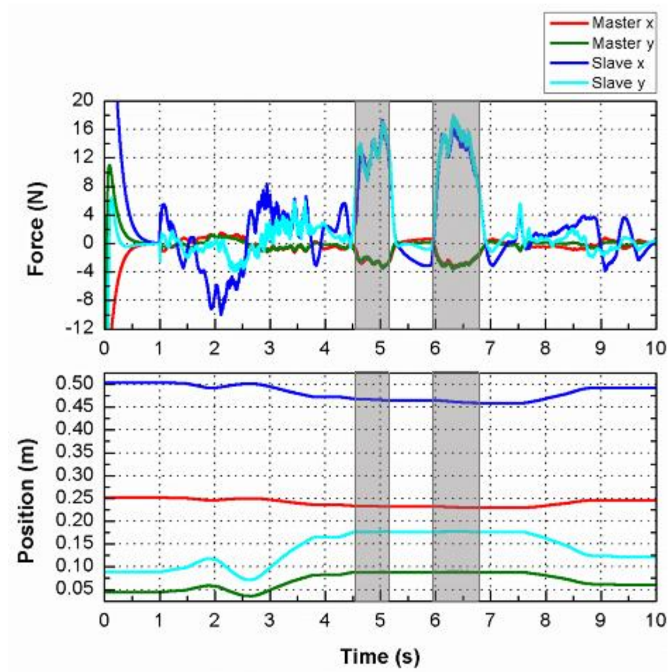

Fig. 7.4. Force and position response during free and contact motion (Case 4)

The differential mode (after dividing by two) for x-axis and y-axis is -4.52 x 10^{-6}m and -1.68 x 10^{-6}m respectively. The position tracking was performed with almost zero mean error, as the values are the same with scaling effect.

D. Case 4

The force for both x and y position tracked at slave system is five times larger than master manipulator as shown in Figure 7.4. This is due to the nominal mass at slave system is set five times larger than master system. If the force response of slave system is divided by five, then the performance of common mode is −0.0206N and 0.0555N for x-axis and y-axis, respectively. As seen in all the cases, Case 4 also proves that the law of action and reaction with scaling effect are achieved between master and slave system.

The performance for differential mode for x-axis and y-axis is -3.18 x 10^{-6}m and 1.43 x 10^{-6}m respectively. Similar with the other cases, position tracking was achieved with almost zero mean error.

E. Comparison of errors between Case 1 to Case 4

To summarize the performance between Cases 1 to 4, Table III shows the achieved common mode and differential mode error, which are small values, indicating success of force scaling. Figures 7.5 to 7.8 shows the varying gains according during motion.

TABLE III

PERFORMANCE RESULTS OF CASE 1 TO CASE 4

Case	Common Mode (Force)		Differential Mode (Position)	
	x-axis	y-axis	x-axis	y-axis
1	−0.0217N	0.0395N	-9.99×10^{-6}m	-2.97×10^{-6}m
2	0.0715N	0.0528N	-2.98×10^{-6} m	-3.29×10^{-6}m
3	−0.0472N	0.0626N	-4.52 x 10^{-6}m	1.68 x 10^{-6}m
4	−0.0206N	0.0555N	-3.18 x 10^{-6}m	1.43 x 10^{-6}m

The performance for common mode for all the cases are generally less than 0.1N in magnitude whereas for differential mode, position mean errors are less than 1×10^{-6}m in either positive or negative errors.

F. Comparison of α gains of Case 1 to Case 4

The scaling ratio, α gain changes with respect to posture or position of the two link manipulator. For example, when the M_{n1} and M_{n2} between slave system is two times larger than the master system, the nominal equivalent mass matrix, M_{xxn} and M_{yyn} between master and slave system are affected. Thus, α consists of x-axis and y-axis with regards to the mass matrix.

The results of the α gain values that changes over time for Cases 1 to 4 can be seen in Figures 7.5 to 7.8.

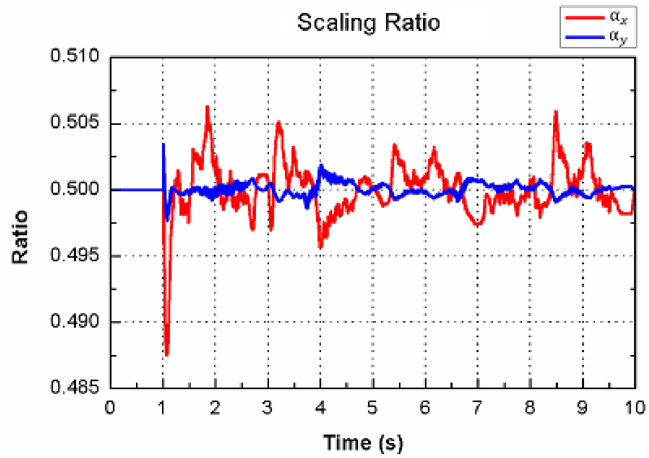

Fig. 7.5. Scaling ratio (α_x and α_y) for Case 1

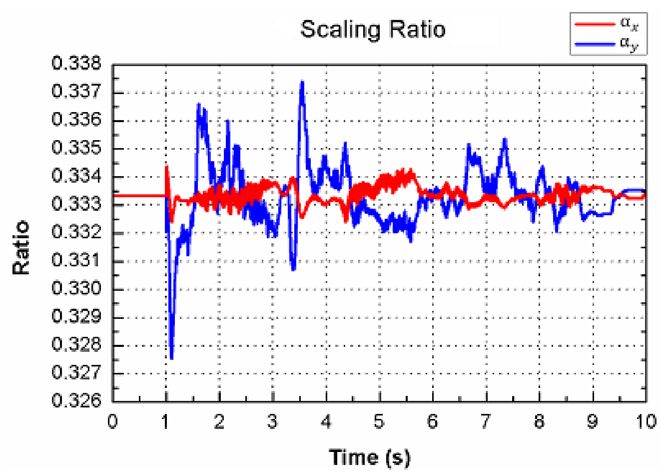

Fig. 7.6. Scaling ratio (α_x and α_y) for Case 2

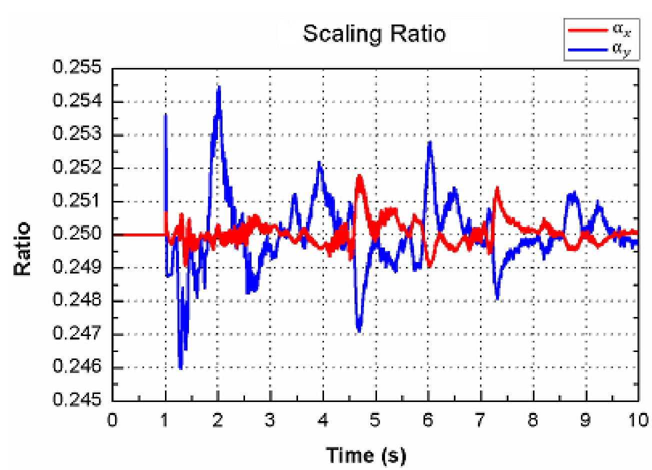

Fig. 7.7. Scaling ratio (α_x and α_y) for Case 3

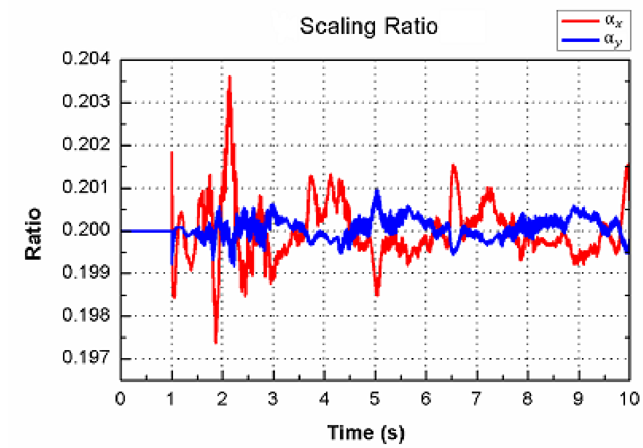

Fig. 7.8. Scaling ratio (α_x and α_y) for Case 4

To summarize the α gain scaling results, Table IV can be referred to. The table shows that the average scaling ratio for Cases 1 to 4 does not deviate much from the ratio of nominal mass ratio scaling.

TABLE IV
SCALING GAIN FOR CASE 1 TO CASE 4

Case	α_x	α_y	M_{Mn}/M_{Sn}	Deviation
1	0.50000	0.500030	1/2 =0.50000	0.00003
2	0.33332	0.333370	1/3 = 0.33333	0.00004
3	0.25000	0.250005	1/4 = 0.25	0.000005
4	0.19998	0.200050	1/5 = 0.2	0.0005

Based on the results in Table IV, it can be seen that the average α gain values which varies over posture and time, is very close to the ratio between master and slave nominal mass. Thus it can be said that the force scaling of this multi degree of freedom manipulator achieved success in the experiments.

VIII. Conclusion

For a multi Degree of Freedom manipulator, force scaling presents interesting interactive motion. From the four cases, it is clearly shown that the force and position tracking (common and differential mode) was achieved with low errors. The forces are scaled according to the nominal mass ratio of master to slave, even though the mass matrix will varies slightly with the respect to the angle of actuation. It is important to note that this method can help scaled to any desired value, as long as it is not larger than the achievable force that the mechanism can handle. It could also be scaled down as long as it is not smaller than the resolution of the force achievable.

Acknowledgement

The Authors wish to express their thanks to the Robotics and Industrial Automation (RIA) Research Group at the Centre of Excellence in Robotics and Industrial Automation (CeRIA), Universiti Teknikal Malaysia Melaka (UTeM) and also the Faculty of Electrical Engineering. We also wish to acknowledge the UTeM Short Term Grants (PJP/2015/FKE(1D)/S01392).

REFERENCES

[1] Y. Toda; N. Kubota "Self-Localization Based on Multiresolution Map for Remote Control of Multiple Mobile Robots,"*IEEE Transactions on Industrial Informatics*, vol. 9, no. 3, pp 1772-1781, 2013. DOI: 10.1109/TII.2013.2261306.

[2] F. Båberg; Y. Wang; S. Caccamo; P. Ögren, "Adaptive object centered teleoperation control of a mobile manipulator," *2016 IEEE International Conference on Robotics and Automation (ICRA).*, pp. 455 - 461, May 2016, DOI: 10.1109/ICRA.2016.7487166

[3] P. Maxwell; D.Larkin; C.Lowrance, "Turning Remote-Controlled Military Systems into Autonomous Force Multipliers," *IEEE Potentials.*, vol. 32, no. 6, pp. 39-43, 2013 DOI: 10.1109/MPOT.2013.2252240

[4] R. R. Murphy; J. Kravitz; S. L. Stover; R. Shoureshi, "Mobile robots in mine rescue and recovery," *IEEE Robotics & Automation Magazine*, pp. 91 – 103, 2009, DOI: 10.1109/MRA.2009.932521

[5] K. Nagatani, S. Kiribayashi, Y. Okada, S. Tadokoro, T. Nishimura, T. Yoshida, E. Koyanagi. Y. Hada, "Redesign of rescue mobile robot Quince–Toward emergency response to the nuclear accident at Fukushima Daiichi Nuclear Power Station on March 2011–," *Proceedings of the 2011 IEEE International Symposium on Safety,Security and Rescue Robotics*, pp. 13-18, Nov 2016, DOI: 10.1109/SSRR.2011.6106794

[6] A. Tobergte, R. Konietschke and G. Hirzinger, "Planning and Control of a Teleoperation System for Research in Minimally Invasive Robotic Surgery," *2009 IEEE International Conference on Robotics and Automation*, pp. 4225-4232, May 2009, DOI: 10.1109/ROBOT.2009.5152512

[7] M. Tavakoli; R. V. Patel; M. Moallem, "A force reflective master-slave system for minimally invasive surgery," IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 3077 – 3082, October 2003, DOI: 10.1109/IROS.2003.1249629

[8] H. Sulaiman, M.N.A. Saadun, A.A Yusof, "Modern Manned, Unmanned and Teleoperated Excavator System," *Journal of Mechanical Engineering and Technology*, vol. 7, no. 1, pp. 57-68, 2015

[9] A.A. Yusof, M.N. Saadun, "Modern Practical Application and Research on Teleoperated Excavators, Control, Feedback and Perception Issues in Post Disaster Recovery Operation," 2015 IEEE International Symposium on Robotics and Intelligent Sensors (IEEE IRIS2015), pp. 179-185, 2015

[10] A.A. Yusof, M.N. Saadun, M.K. Nor, M. Q. Ibrahim and M. Z. Hanafi "Position control analysis and operational evaluation of teleoperated electro-hydraulic actuator (TEHA)", Int. Integrated Engineering Summit. Batu Pahat, Malaysia, 2014, pp. 10-16.

[11] K. Kaneko, H. Tokashiki; K. Tanie; K. Komoriya, "Macro-micro bilateral teleoperation based on operational force feedforward," *Proceedings of the 1998 IEEE/RSJ International Conference on Intelligent Robots and Systems, October 1998*, pp.1761–1769. DOI: 10.1109/IROS.1998.724852

[12] K. Takeo; K. Kosuge, "Implementation of the micro-macro teleoperation system without using slave-side force sensors," 1997 IEEE International Conference on Robotics and Automation, pp. 1600-1605, 1997. DOI: 10.1109/ROBOT.1997.614369

[13] A. Sano, H. Fujimoto, T. Takai, "Personal scaling on micro-teleoperation," *Proceedings of the 26th IEEE Anual COnference of the IEEE Industrial ELectronics Society, IECON '00*, pp.7–12. 2000. http://dx.doi.org/10.1109/IECON.2000.973118

[14] T. Shimono, K. Ohnishi, "Reproduction of real world force sensation by micro-macro bilateral control with respect to standardized modal space," *IECON Proceedings (Industrial Electronics Conference)*, pp.374–379, 2007 http://dx.doi.org/10.1109/IECON.2007.4460092

[15] T. Shimono, S. Katsura, S. Susa, T. Takei, K. Ohnishi, "Transmission of force sensation by micro-macro bilateral control with respect to standardized model space," *Proceedongs of International Conference on Mechatronics*, 2007, pp. 1-6, http://dx.doi.org/10.1109/ICMECH.2007.4280061

[16] S. Sua, T. Shimono, "Transmission of force sensation by micro-macro bilateral control with scaling of control gains," *International Workshop on Advanced Motion Control*, 2008, pp.532–537. http://dx.doi.org/10.1109/AMC.2008.4516123

[17] S. Susa, K. Natori, K. Ohnishi, "Three-channel micro-macro bilateral control system with scaling of control gains," Proceedings - 34th Annual Conference of the IEEE Industrial Electronics Society, 2008, pp.2598–2603 http://dx.doi.org/10.1109/IECON.2008.4758366

[18] N. Motoi, R. Kubo, T. Shimono, K. Ohnishi, "Bilateral Control with Different Inertia Based on Modal Decomposition," 11th IEEE International Workshop on Advanced Motion Control, AMC 2010, pp.697–702. http://dx.doi.org/10.1109/AMC.2010.546404

[19] L.J. Wei, A.Z. Shukor, M.H. Jamaluddin, "Workspace Control of Two Link Planar Robot using Micro-Box 2000," *Jurnal Teknologi*, vol. 77, no. 20, 2015.

[20] K. Ohnishi, S. Katsura, and T. Shimono, "Motion Control for Real World Haptics," *IEEE Ind. Electron. Mag.*, vol. 4, pp. 16–19, 2010.

[21] K. Ohnishi, N. Matsui, and Y. Hori, "Estimation, Identification, and Sensorless Control in Motion Control System," *Proc. IEEE*, vol. 82, no. 8, pp. 1253 – 1265, 1994.

[22] T. Murakami and K. Ohnishi, "Torque Sensorless Control in Multidegree-of-Freedom Manipulator," *IEEE Trans. Ind. Electron.*, vol. 40, no. 2, pp. 259–265, 1993.

[23] M. H. Jamaluddin, T. Shimono, and N. Motoi, "An Integration Method between Vision-based Disturbance Observer and Bilateral Haptic System for Robust Tracking of Target Object," *IEEE 13th Int. Work. Adv. Motion Control (AMC), 2014*, vol. 0, no. 1, pp. 723–728, 2014.

[24] S. Katsura, Y. Matsumoto, and K. Ohnishi, "Modeling of Force Sensing and Validation of Disturbance Observer for Force Control," *Proc. 29th Annu. Conf. IEEE Ind. Electron. Soc. IECON '03*, vol. 54, no. 1, pp. 530–538, 2007.

[25] O. Ozen, E. Sariyildiz, H. Yu, K. Ogawa, K. Ohnishi, and A. Sabanovic, "Practical PID Controller Tuning for Motion Control," *2015 IEEE Int. Conf. Mechatronics*, pp. 240–245, 2015.

[26] E. Sarlyildlz and K. Ohnishi, "A Comparison Study for Force Sensor and Reaction Force Observer based Robust Force Control Systems," *2014 IEEE 23rd Int. Symp. Ind. Electron.*, pp. 1156–1611, 2014.

[27] L. J. Wei, A.Z. Hj. Shukor, M.H. Jamaluddin, "Investigation on the Effects of Outer-Loop Gains, Inner-Loop Gains and Variation of Parameters on Bilateral Teleoperation Control System Using Geared DC-Motor," International Journal of Mechanical and Mechatronics Engineering, vol. 16, no. 1, pp. 54-69, 2016.