International Journal of Robotics and Automation (IJRA)
Vol. 1, No. 1, March 2012, pp. 1~12
ISSN: 2089-4856

Design and Experiments of Low Cost Teleoperation System

Adha Cahyadi* **, Ng Khin Hooi, Anugrah Persada**, Rubiyah Yusof** and Yoshio Yamamoto*****
* Departement of Electrical Engineering and Information Technology, Universitas Gadjah Mada, Yogyakarta, Indonesia
** Centre for Artificial Intelligence and Robotics (CAIRO), Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia
*** Department of Precision Engineering, School of Engineering, Tokai University, Kanagawa, Japan

Article Info

Article history:

Received Jan 16, 2012
Revised Mar 17, 2012
Accepted Mar 21, 2012

Keyword:

Low cost teleoperation system
PID
System identification
SCARA
Position Control

ABSTRACT

In this work, a teleoperation system consists of two planar SCARA manipulators is developed. The manipulators are constructed using basic low cost aluminum bars as well as cheap electronic circuitry and software. Modeling, system identification, individual control and teleoperation control are proposed. Finally, experiments are also performed to verify the effectiveness of the design.

Corresponding Author:

First Author
Departement of Electrical Engineering and Information Technology
Universitas Gadjah Mada, Yogyakarta, Indonesia
Email: adha.imam@ugm.ac.id

1. INTRODUCTION

Teleoperation has been used in many applications ranged from military, medical, biological, industrial to space applications (Sanders, 2006), (Kapoor and Tesar, 2006), (Hainsworth, 2001), (Parrish et al, 2001), (Madani et al, 2008), (Sitti, 2003). These show that the researches in teleoperation are important and chalenging. However, mostly the design of teleoperation systems is difficult, tasks-specific and expensive to fabricate. However, for educational purpose, benchmarking and simple tasks a cheap and easy-to-develop teleoperation systems are inevitably needed. On the other hand, many robots operated in the industry for instance SCARA, Stanford manipulator, articulated arm etc., do not have capability to be applied as teleoperation system. In the industry, beside automatically operated, robots sometimes have to undergo operator operated, for example by using teach pendant or joystick for specific tasks. Based on these situations, one may think that if we are able to compose a teleoperation system using two industrial robots, a cheap teleoperation system for industrial and laboratory purposes can be constructed easily.

In a common setting, a teleoperation system as shown in Fig. 1, the operator will exert force on the master manipulator which in turn, results in a displacement or velocity that is transmitted to the slave side as the order or command. In order to sense the manipulated object, some informations have to be returned from the slave side to the operator side. These information could be distance measurement, velocity measurement, force measurement or their combination. A teleoperation system as shown in Fig. 1 has to be able to "actuating while sensing" means while exerting force from its actuator, the force itself has to be acquired and sent to the other side either master or slave side. Unfortunately, a commercially fabricated robots for industrial purposes usually do not come with this feature. Thus they need to be further prototyped in order to have this capability.

The main objective of this proposed research work is to design and implement such kind of teleoperation system so that it is possible to use the commercially available robots in the market as teleoperation system. Being its simple structure and design, since 1964 the SCARA robot has been widely used in the industry. Moreover, due to its importance, many works have been done related to the SCARA robots especially in production and fabrication (Craig, 2005). In view of the above informations, in this work a pair of SCARA robot will be designed and prototyped in order to set up a teleoperation system.

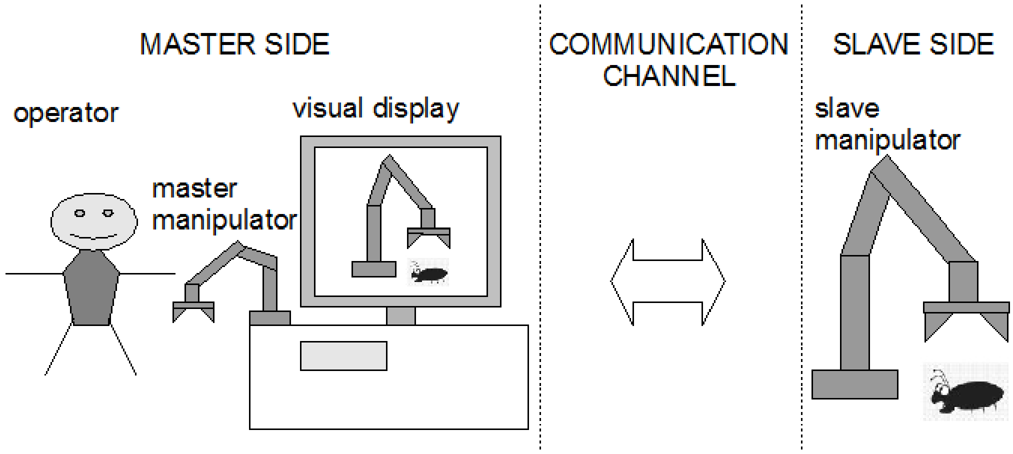

Figure 1. Illustration of a teleoperation system

2. MECHANICAL DESIGN

2.1. D-H COnvention

In this paper, the D-H convention (Denavit and Hartenberg, 1955) is used especially to find the forward and inverse kinematics of the robot. The design of the manipulators with the choice of D-H parameters is shown in Fig. 2, while the one developed in the laboratory is shown in Fig. 3. The D-H parameters in this paper are denoted as follows

a_i= the distance from Z^i to Z^{i+1} measured along X^i
α_i= the distance from Z^i to Z^{i+1} measured along X^i
d_i= the distance from X^{i-1} to X^i measured along Z^i
θ_i= the distance from X^{i-1} to X^i measured along Z^i.

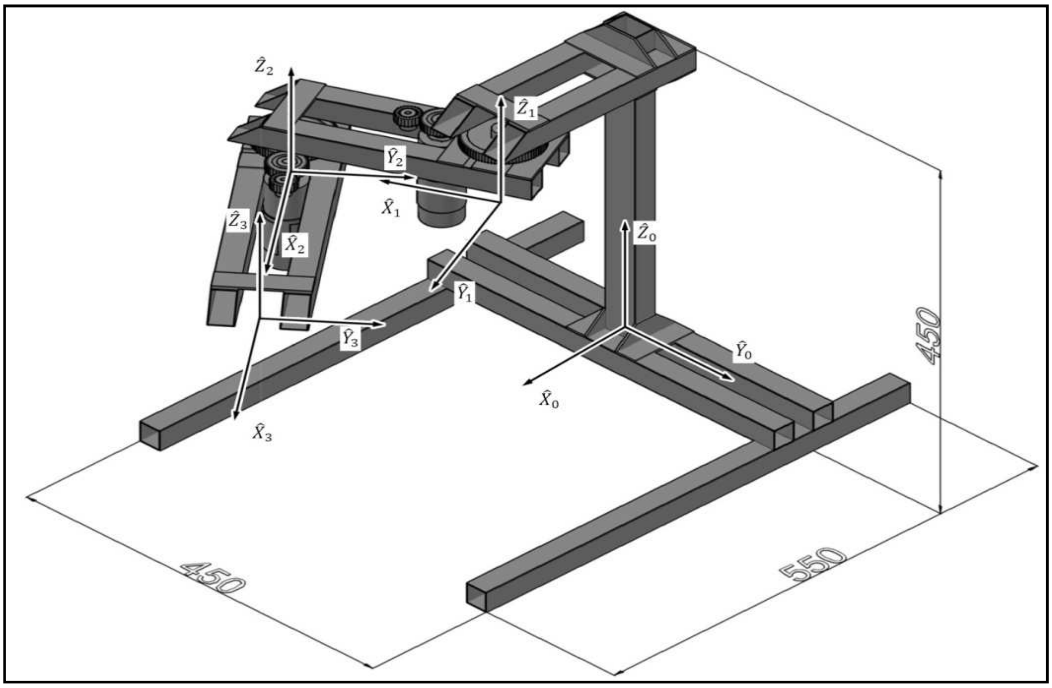

Figure 2. Design of SCARA arm

Figure 3. developed arm in the laboratory

The base frame as shown in Fig. 4 is placed on the floor level and the Z-axis is placed parallel with the main support of the robot arm. On the other hand, the end effector is placed at the end and frame for link 1 and link 2 is placed in the same plane as $Z^3 = 0$. By doing this, the value of d_2 and d_3 can be zeroed. After the placement of the frames, the D-H parameters are shown in Table 1. The homogenous transformation could be obtained based on the four parameters as follows

$$ {}^0_3T = \begin{bmatrix} c_1c_2 - s_1c_2 & -c_1s_2 - s_1c_2 & 0 & 0.24(c_1c_2 - s_1c_2) + 0.21c_1 + 0.16 \\ s_1c_2 + c_1s_2 & -s_1s_2 + c_1c_2 & 0 & 0.24(s_1c_2 + c_1s_2) + 0.12s_1 \\ 0 & 0 & 1 & 0.27 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

where ${}^0_3T$ is the transformation from 0th- axis to 3rd-axis, $c_{1,} c_2, s_{1,}$ and s_2 stand for $cos\theta_1, cos\theta_2, sin\theta_1$ and $sin\theta_2$, respectively.

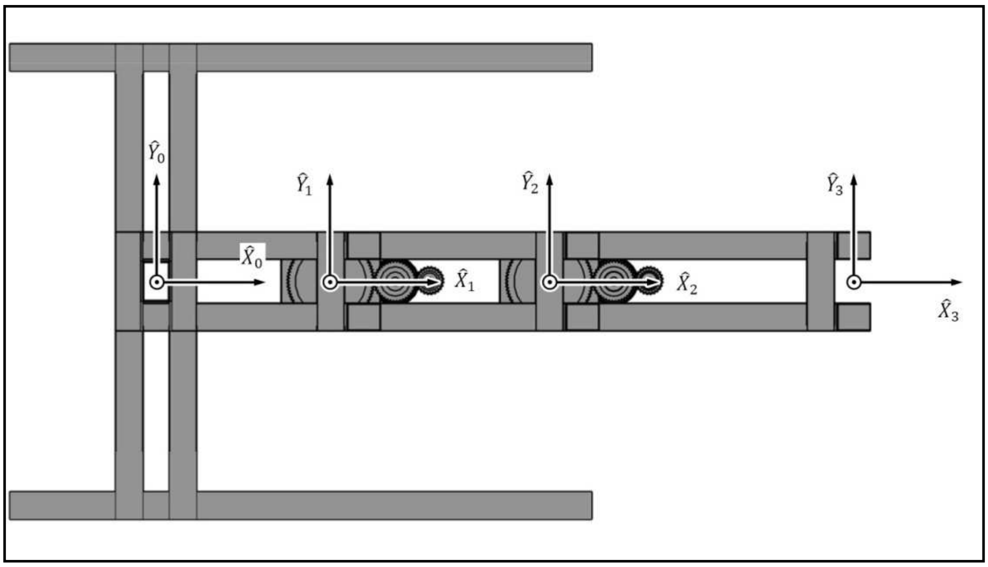

Figure 4. Placement of frame on the robot

Table 1. D-H parameters

i	α_{i-1}(rad)	a_{i-1}(m)	d_i(m)	θ_i(rad)
1	0.0	0.16	0.27	θ_1
2	0.0	0.21	0.00	θ_2
3	0.0	0.24	0.00	0.0

2.2 Interfacing Circuitry

To drive the robot arm, a low cost electronic circuit is built to interface the hardware and software. For angular displacement sensor, a multi-turn potentiometer is used. As the sensor is noisy, the voltage regulator and the anti-aliasing filter are proposed as shown in Fig. 5 and Fig. 6.

The voltage regulator, as shown in Figure 4, regulates the voltage from a power supply to provide the multi-turn potentiometer a stable voltage ranging from 0 to 5 volts. A diode was used as a circuit protection is the power supply terminals were to be switched and the capacitors were placed to produce stable voltage output.

As shown in Figure 6, an anti-aliasing low pass filter is used to filter out high frequency noise in the multi-turn potentiometer. Cut-off frequency of 15.9 Hertz is chosen for the filter. The first operational amplifier acts as a voltage buffer for the multi-turn potentiometer. This is to prevent from voltage side-loading effect where the voltage reading will be non-linear with the rotation of the arm. The second operational amplifier acts as an active 1st-order filter.

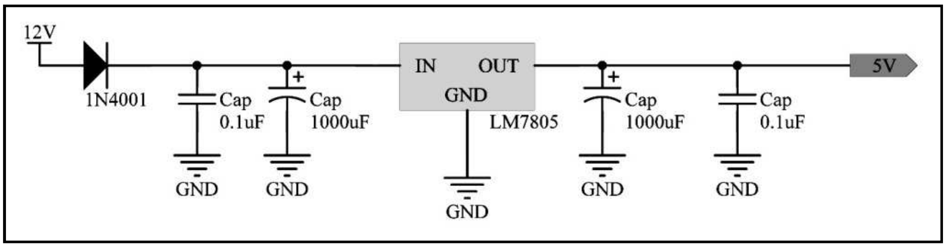

Figure 5 Voltage regulator using LM7805

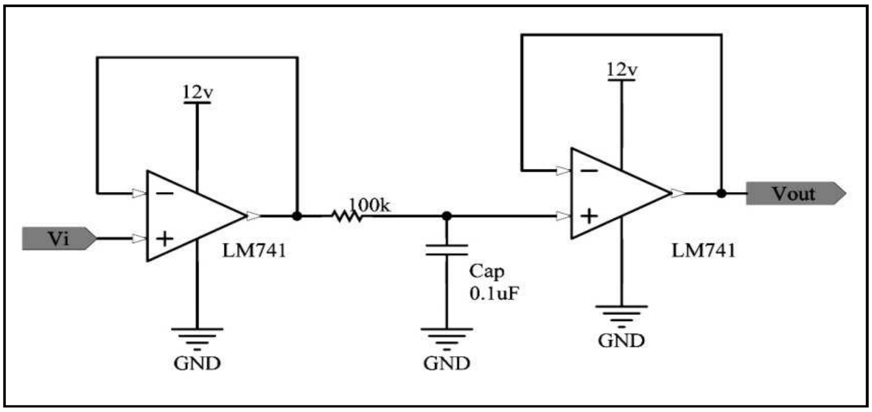

Figure 6. Anti-aliasing low pass filter with voltage buffer

For torque measurement, a current sensing sensor ACS714 from Allegro MicroSystems Incorporated is proposed. Using current, usually the torque of the motor could be estimated by using a linear function interpolation. Beside that the current could be used as a feedback loop for the controller.

For the actuator interface, a motor driver from Dimension Engineering, i.e., Sabertooth 2X12 driver is used. As each driver can support two motors, only one driver is necessary to drive a single arm. This driver is used along with the current sensor where the current sensor is connected in series with the motor. Both sensors and actuators are then connected to the NI-USB 6008 to interface with LabView from National Instruments that is used as the main controller.

3. MODELLING IDENTIFICATION AND CONTROL

3.1 Parameter identification

In this section, the identification of electrical parameters of the permanent magnet DC motor is discussed. Firstly, the mechanical model is derived. Then the parameter identification is done using Matlab Identification Toolbox. The permanent magnet direct current motor model used in this work is depicted in Fig. 7.

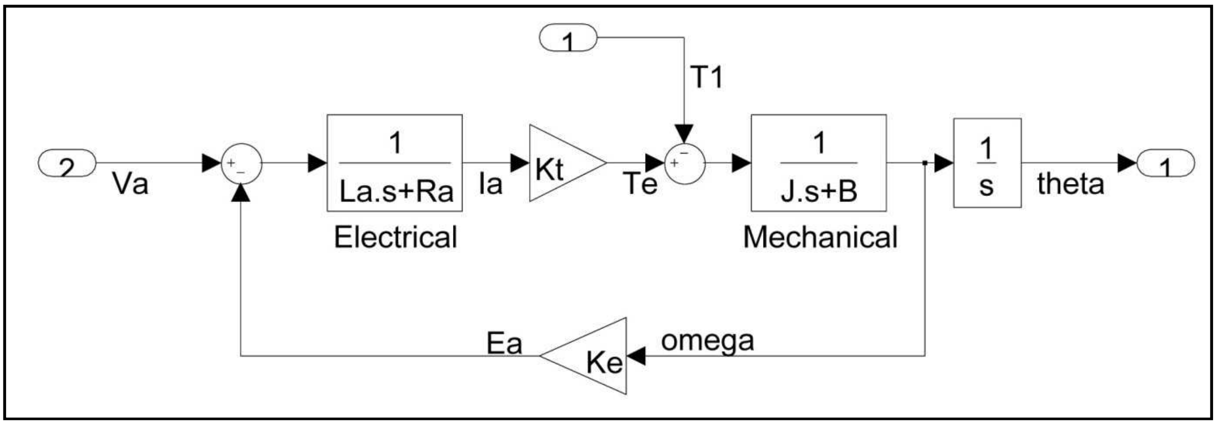

Figure 7. Permanent magnet direct current motor model

The motor resistance, $R_a$and inductance $L_a$are identified by giving external stimulus at V_a while observing the current I_a. If the disturbance torque T_1 is assumed to be zero then the fitting model can be derived from the motor model as follows

$$E_a = K_e\left(\frac{K_t I_a}{Js+B}\right) \quad (2)$$

$$I_a = (V_a - E_a). \quad (3)$$

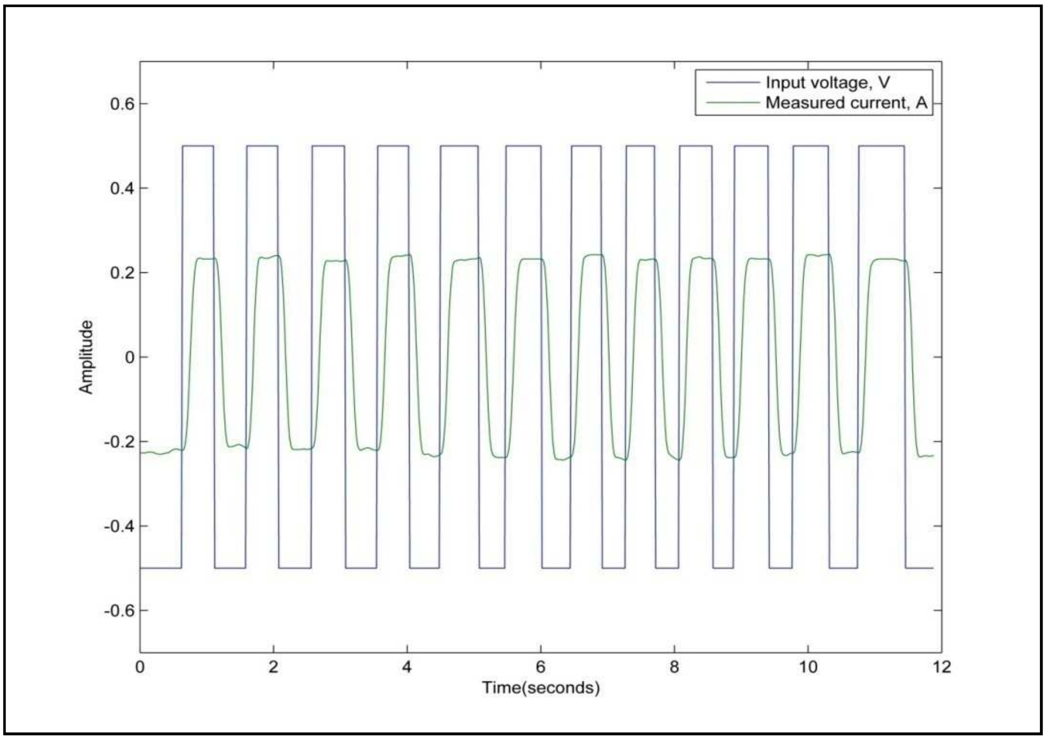

Figure 8. Plot of the external voltage stimulus and the measured output

Substituting (1) in (2) and rearranging we get

$$\frac{I_a}{V_a} = \frac{Js+B}{JL_a s^2+(JR_a+BL_a)s+(BR_a+K_e K_t)}. \tag{4}$$

Due to nonlinearity in the disturbance torque, T_1, (3) will be no longer valid and become too complex to identify. To be easier, the motor is stalled, i.e., to set $\omega = 0$. Thus, the fitting model will be just

$$\frac{I_a}{V_a} = \frac{1}{L_a s+R_a}. \tag{5}$$

Therefore, the motor will be excited with voltage stimulation to obtain the overall motor parameters. After, external stimulation is given to V_a and motor position, θ is measured. The fitting model is given by

$$\frac{\theta}{V_a} = \frac{K_t}{s\left(JL_a s^2+(JR_a+BL_a)s+(BR_a+K_e K_t)\right)} \tag{6}$$

Unfortunately, the model is not expected to perfectly fit due to the disturbance torque at T_1. Some of the examples of disturbance torque are gravity which in this case, is zero because of the arm design, and *Coulomb* friction.

3.1.1 Motor Electrical Characteristics

As discussed before, the motor is stalled to make zero back electromotive force. By doing so, the motor resistance and inductance can be identified using a first order fitting model. Using LabView NI-USB 6008 to acquire the data and identified using the Matlab System Identification Toolbox for identification, the model for electrical characteristics is obtained as follows

$$\frac{I_a}{V_a} = e^{-0.056s}\frac{1}{0.115s+2.113} \tag{7}$$

where, $R_a = 2.113$ and $L_a = 0.115$.

3.1.2 Motor Mechanical Characteristics

After obtaining the electrical characteristics, the motor mechanical characteristic will also be derived as well.

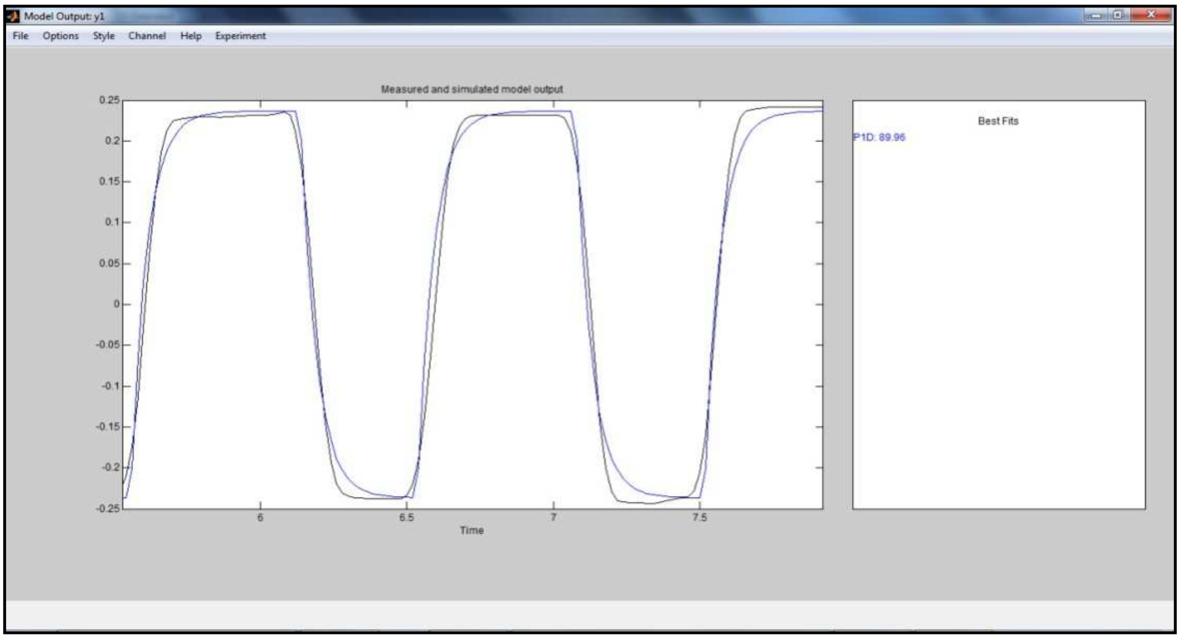

Figure 9 Current loop best fitting value, 89.96%

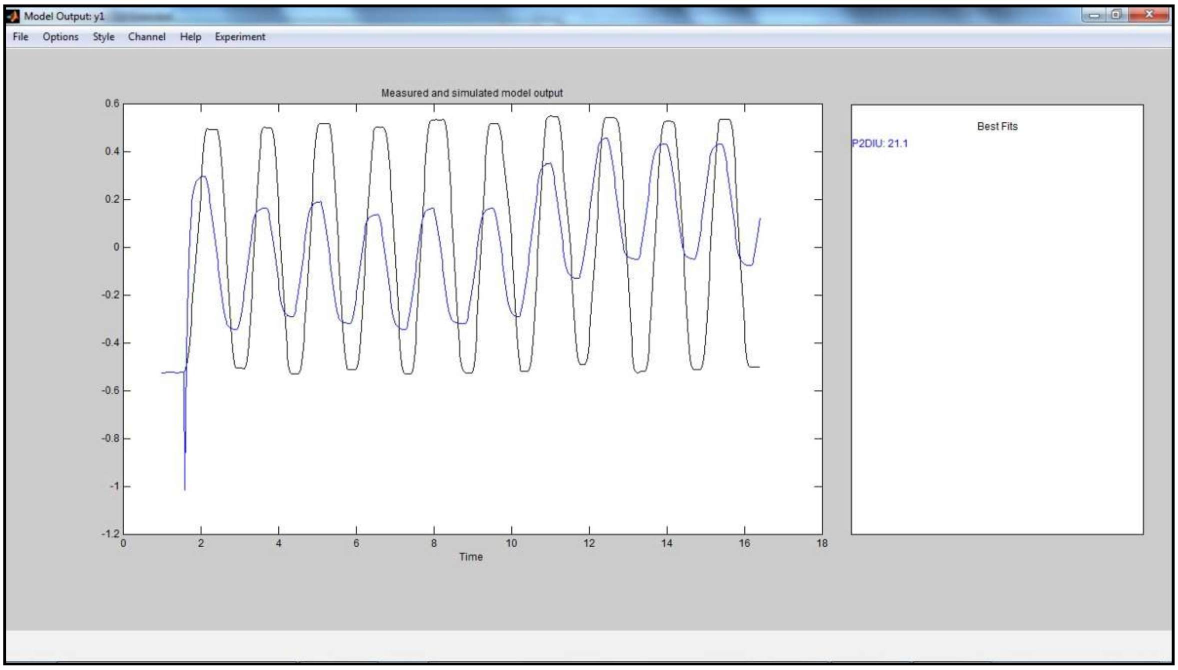

Figure 10. Fitting model for mechanical model

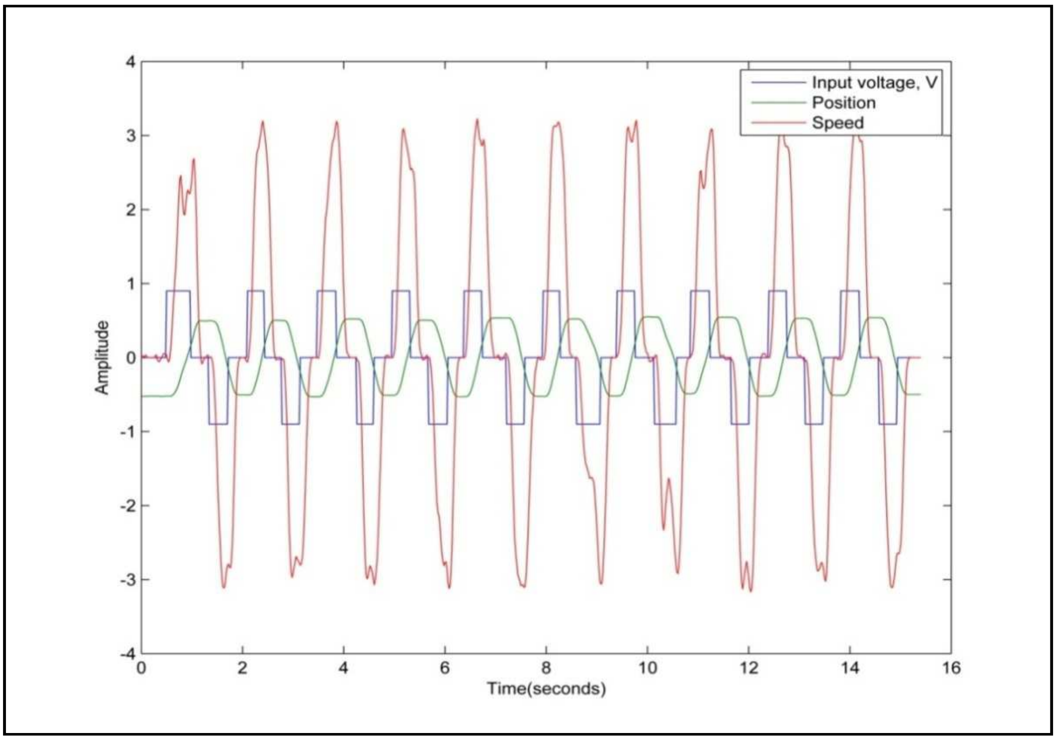

Figure 11. Plot of the external voltage stimulus and the measured output

By using the same step, as shown in Fig. 10, the fitting for the total motor model is found to be unacceptable. This is due to the initial value is not being estimated well. To solve this, the motor position data is differentiated once using five points first derivative central method in order to get

$$\frac{\omega}{V_a} = \frac{K_t}{JL_a s^2+(JR_a+BL_a)s+(BR_a+K_eK_t)}. \qquad (8)$$

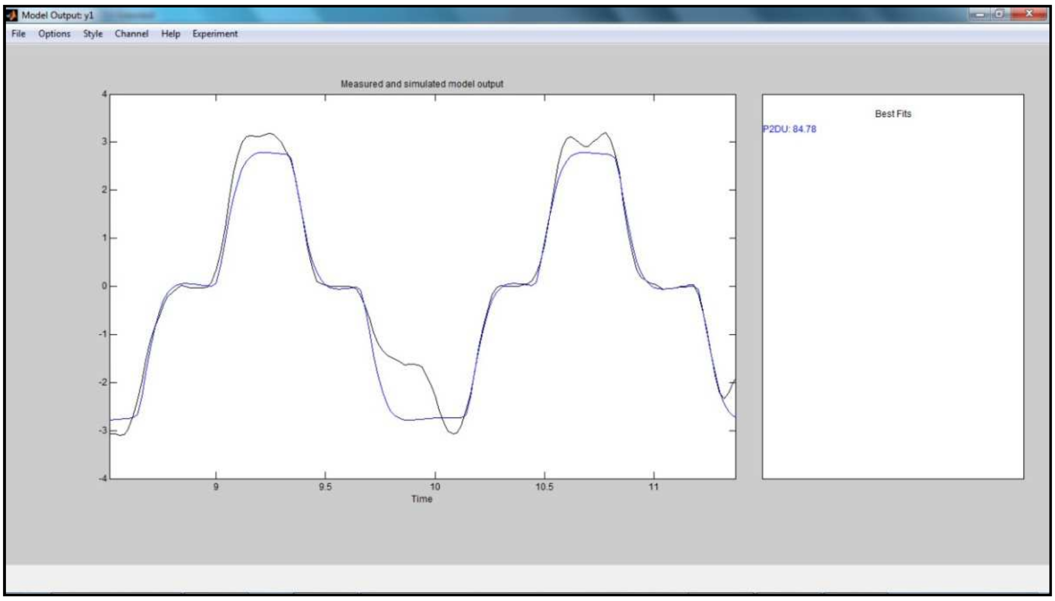

Figure 12. Motor model best fit, 84.87%

After doing the similar process, the identified model for the total system is given as follows

$$\frac{\omega}{V_a} = e^{-0.049s}\frac{1458}{s^2+34.08s+480.2} \tag{9}$$

where $K_t = 153.846$, obtained from datasheet, $K_e = 0.131, J = 0.918$ and $B = 14.418$.

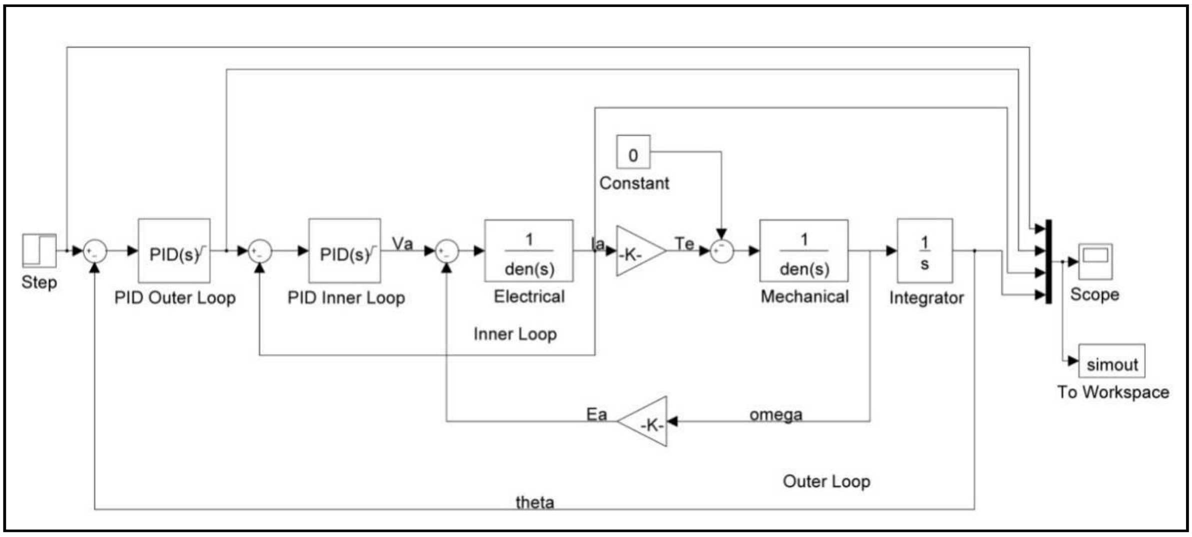

Figure 13. Proposed cascaded control for motor position

3.2 Robot Dynamics

From the kinematics of the arm as discussed before, the dynamics are given as follows

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta}) = u - \tau_e \tag{10}$$

where u is the control input torque, τ_e is the torque due to interaction with the environment and other external forces, and

$$M(\theta) = \begin{bmatrix} p_1 + 2p_3c_2 & p_2 + p_3c_2 \\ p_2 + p_3c_2 & p_2 \end{bmatrix} \tag{11}$$

$$C(\theta,\dot{\theta}) = \begin{bmatrix} -p_3\dot{\theta}_2(2\theta_2+\theta_2)s_2 \\ p_3\theta_1^2 s_2 \end{bmatrix} \quad (12)$$

where

$$p_1 = I_1 + I_2 + I_3 + I_4 + I_p + (M_1 + M_2 + M_p){L_1}^2 + M_2{L_3}^2 + M_4{L_4}^2 + M_p{L_2}^2$$
$$p_2 = I_3 + I_4 + I_p + +M_4{L_4}^2 + M_p{L_2}^2$$
$$p_3 = M_4L_1L_4 + M_pL_1L_2$$

with I_1, $I_2, I_3, I_4, I_p, M_1, M_2, M_3$, M_p, L_1, L_2, L_3, L_p are respectively, the inertias, masses, and lengths of the respective links.

3.3. Position Control

In this paper, cascade controller is demonstrated to control the position of the joint separately, i.e., only one joint is considered and the other joints are kept fixed to prevent it affected by Coriolis and Centrifugal terms. Cascade controller has advantages compared to single loop design. Few of the advantages are better disturbance rejection and faster response due to better response in the inner loop (Astrom & Hagglund, 1995) and (Visioli, 2006).

For the cascade control, the inner loop control is the current control loop while the outer loop is the position control of the joint. PID controller based on Ziegler-Nichols is designed based on the identified model and tuned using simulation software. LabView from National Instruments is used to implement the controller. For simplicity, only proportional gain is used in both PID controllers. The current controller is tuned to 2.3522 while the position controller is tuned to 0.32264. The gains are obtained from the MATLAB SISO Toolbox based on Ziegler-Nichols frequency response tuning. The results depicted in Fig. 14 shows that the position can be controlled well.

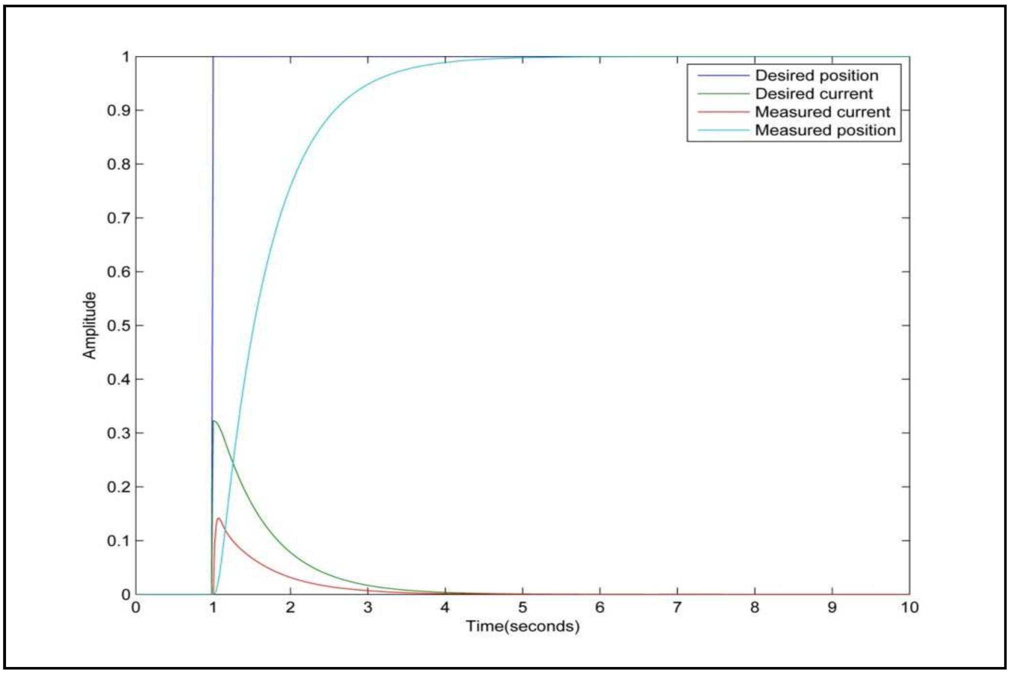

Figure 14. response of the motor position

4. TELEOPERATION SYSTEM DESIGN

In this section the design of teleoperation mode is discussed. We are going to consider two identical SCARA robots (7) for both master and slave sides. For controller design simplicity, our teleoperation system either in the slave side or in the master side is re-written as follows

$$\frac{d}{dt}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} x_2 \\ -M(\theta)^{-1}\{C(\theta,\dot{\theta})\dot{\theta} - u + \tau_{ed}\} \end{bmatrix} \quad (13)$$

where the external forces term τ_{ed} is coming from the direct interaction from the environment in the slave side or from the human force in the master side. It also reflects the interaction forces sent from the other side where the subscript d means that the information is delayed . For coordination control, it is necessary for the control law u as a function of the state from the other side. In this preliminary work, we only consider simple PID control for both master and slave manipulators as follows

$$u_m = k_{pm}(x_m - x_{sd}) + k_{im}\int_0^t \big(x_m(\sigma) - x_{sd}(\sigma)\big)d\sigma + k_{dm}(\dot{x}_m - \dot{x}_{sd}) \quad (14)$$

$$u_s = k_{ps}(x_s - x_{md}) + k_{is}\int_0^t (x_s(\sigma) - x_{md}(\sigma))d\sigma + k_{ds}(\dot{x}_s - \dot{x}_{md}). \quad (15)$$

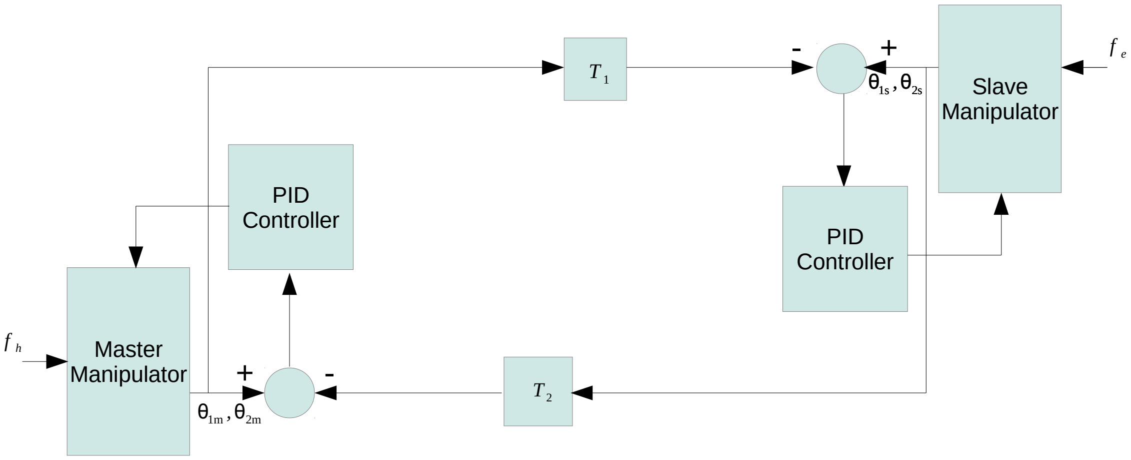

Figure 15. Teleoperation scheme

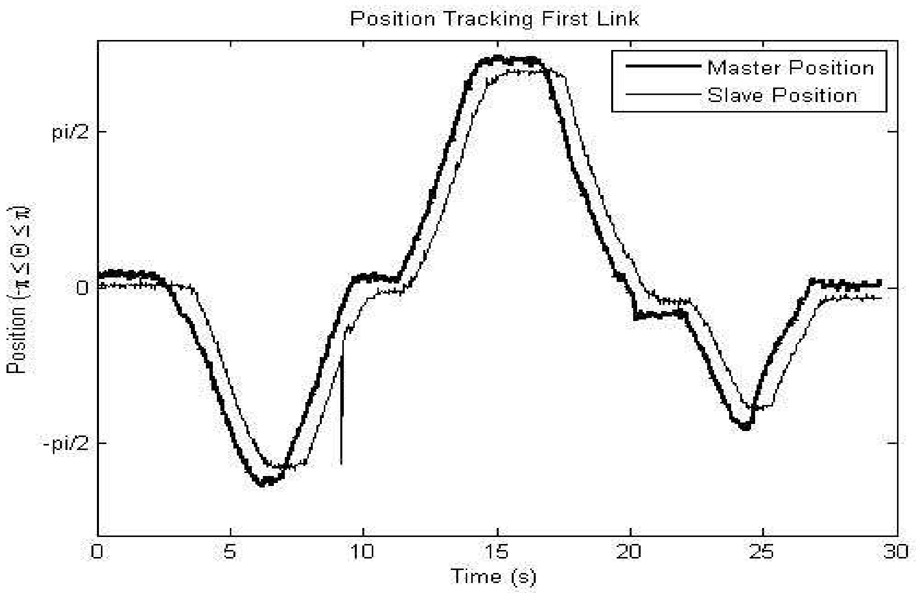

Figure 16. Tracking response of the first link

The structure of the teleoperation system can be seen in Fig. 15. The controllers parameters k_p, k_i and k_d for both master and slave manipulators are respectively set to 5, 1, 2 for link 1 and 8, 2, 3 for link 2. As the master and slave may be located in a distance, the User Datagram Protocol (UDP) connection with approximately 1 second delay is implemented. The tracking results for the first and second link are shown in

Fig. 16 and 17 respectively. From the figures it is seen that in spite of position error and drift, the slave manipulator could track the master manipulator satisfactory.

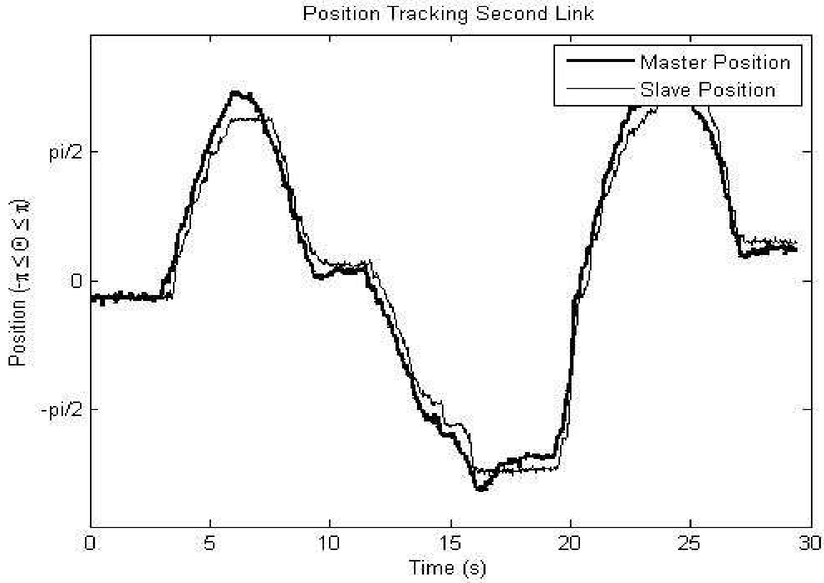

Figure 17. Tracking response of the second link

5. CONCLUSION

In this paper, we developed cheap teleoperation system consists of two identical SCARA Manipulator using basic items like aluminium bars and DC motors. Basic circuitry was also constructed to interface the hardware with software. After modelling and identification, simple position control was also performed. Finally, simple scheme for teleoperation system is designed and implemented. The experimental results showed that the design and control of our teleoperation system is effective. In the future, advanced scheme for teleoperation system is going to be performed. The analysis should be not only on the stability of the teleoperation system but also deeper into the transparency issue. Moreover, some nonlinear terms such as friction will be considered in the modelling.

ACKNOWLEDGEMENTS

The authors would like to express their sincere apreciation to the Ministry of Higher Education (MoHE) Malaysia and Universiti Teknologi Malaysia for providing the financial support for this work under the Tier 2 Research University Grant vot number Q.J130000.2523.03J88.

REFERENCES

[1] Astrom, K. J., & Hagglund, T. (1995). PID Controllers (2nd ed.). USA: Instrument Society of America.
[2] S. Sanders, “Remote operations for fusion using teleoperation,” Industrial Robot, vol. 33, pp. 74–177, 2006.
[3] C. Kapoor and D. Tesar, “Integrated teleoperation and automation for nuclear facility cleanup,” Industrial Robot, vol. 33, pp. 469–484, 2006.
[4] D. Hainsworth, “Teleoperation user interfaces for mining robotics.,” Autonomous Robots, vol. 11, no. 1, 2001.
[5] J. Parrish, D. Akin, and G. Gefke, “The ranger telerobotic shuttle experiment: implications for operational eva/robotic cooperation,” Proceedings of 30th International Conference on Environmental Systems, (Toulouse, France), 2000.
[6] M. Sitti and H. Hashimoto, “Teleoperated touch feedback from the surfaces at the nanoscale: Modeling and experiments,” IEEE/ASME Transactions on Mechatronics, vol. 8, no. 2, pp. 287–298, 2003.
[7] Craig, J. J. (2005). Introduction to Robotics Mechanical and Control. USA: Pearson Education Inc.
[8] Denavit, J., & Hartenberg, R. S. (1955, June). A Kinematic Notation for Lower-Pair Mechanisms Based on Matrices. Journal of Applied Mechanics, 215-221.
[9] Visioli, A. (2006). Practical PID Control. London: Springer-Verlag London Limited.

BIBLIOGRAPHY OF AUTHORS

Adha Imam Cahyadi got his undergraduate degree in Electrical Engineering from Universitas Gadjah Mada, Yogyakarta Indonesia in 2002. After a year working in industry such as in Matsushita Kotobuki Electronics and Halliburton Energy Services as engineer, he pursued his master degree in Control Engineering from KMITL Thailand and graduated in 2005. Later he obtained Doctor of Engineering from Tokai University Japan in 2008. His research interests are in teleoperation systems and robust control for delayed systems especially process plant. Currently he is a lecturer at the Department of Electrical Engineering and Information Technology, Universitas Gadjah Mada and a visiting lecturer at the Centre for Artificial Intelligence and Robotics (CAIRO), Universiti Teknologi Malaysia, Malaysia.

Ng Khin Hooi was born in 18 August, 1988. He is now currently pursuing his studies in Degree in Engineering (Electrical - Mechatronics) and now is undergoing his final year. During his studies in degree level, he participated in the Asia Pacific Broadcasting Union Robot Contest for two years and represented Malaysia in Cairo, Egypt (2010) and Bangkok, Thailand (2011). His research interest is in controls, robotics and digital signal processing. In 2011 he joined Centre of Artificial Intelligence and Robotics (CAIRO) for his internship.

Anugerah Galang Persada was born in 1987. He got his first degree from Electrial Engineering Department Universitas Gadjah Mada in 2005 major in Control Engineering. Later he became lecturer at Bugs Training Center, Yogyakarta Indonesia in 2010. In 2011 He joined Centre of Artificial Intelligence and Robotics (CAIRO) as research assistance. His main interests are in control application such as in teleoperation systems, process control, and electrical machines.

Rubiyah Yusof completed his bachelor degree from University of Laughborough in United Kingdom major in Electrical and Electronics. She obtained master and PhD degree Crankfield Inst. of Tech., UK in 1986 and the University of Tokushima, Japan in 1994, respectively. Since 1983 she has been with the Faculty of Electrical Engineering, Universiti Teknologi Malaysia where she is now a professor. She also served as the Director of Centre for Artificial Inteillgence and Robotics (CAIRO) until now. She has more than one hundred publications in international journals as well as in book chapters and one book about artificial intelligence. Her main research interests are in adaptive control, artificial intelligence and its application and in biometrics application.

Yoshio Yamamoto was born in 1958. He obtained his B.Eng and M.Eng degree, both from Tokyo University,in 1981 and 1983, respectively. He joined Furukawa Electric Co. Ltd. as a R&D engineer and earned M.Sc in computer science and Ph.D. from Columbia University, USA in 1989 and from University of Pennsylvania in 1994, respectively. In 1994 he joined Ibaraki University as a research associate, and then moved to Department of Precision Engineering of Tokai University as an associate professor in 1998 where he currently is a professor. His research interests include coordination and control of wheeled mobile manipulator, outdoor navigation of autonomous mobile robots, applications of haptic interface, and applications of giant magnetostriction materials.