A Prototyping of 2-DOF Robot Arm Using Feedback Control System

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***Abstract*—Robotic technology is rapidly developed. One type of robots commonly used in industry scale is a robotic manipulator or a robot arm. In this paper, a prototype of 2-DOF robot arm is designed by using Solidworks and built. The joints are driven by permanent magnet DC motor coupled with encoders. The prototype is controlled by feedback control system with PID controller that was obtained by parameter estimation and PID tuning and has been tested by the RAPCON platform with MATLAB-Simulink. The tracking results are the responses at different reference input. First, at 60 and 90 degree reference input, both motors respond over the reference input with maximum overshoot less than 21 degree of maximum overshoots, rise time does not exceed 2 second and steady-state errors range from 14% to 21%. Second at 15 or 30 degree reference input, both motors were unable to reach the reference input and had steady-state errors range from 20% to 25%. The error occurs because of the friction of worm gearbox and the control of armature voltage.**

Keywords-2DOF-robot arm; feedback control system; inverse kinematics; PID-controller

I. INTRODUCTION

Robotic technology is rapidly developed. Many industries are moving from their current state of automation to robotization, to increase productivity and derive uniform quality. Robots and robot-like manipulators are now commonly employed in hostile environment, such as an atomic plant to handle radioactive materials. Moreover, robots are being employed to construct and repair space stations and satellites. It seem to be impossible to put up an exhaustive list of robot applications. However, one type of robots commonly used in industry scale is a robotic manipulator or a robot arm. It is an open or closed kinematic chain of rigid links interconnected by movable joints. [1]

According to Thailand 4.0, an economy model of Thailand, Robotics is one of the ten targeted industries. Suranaree University of Technology has many industrial robot arms for education such as SCALAR robot arm as shown in Fig. 1 but does not have a robot arm with the control system. In the control system areas, the PID controller has been widely used because of its simplicity and effectiveness. [2] Therefore, in this paper, a prototype of robot arm is developed for education in Suranaree University of Technology.

Figure 1. A SCARA robot arm at Suranaree University of Techonology, Thailand.

II. KINEMATIC MODELLING OF 2-DOF ROBOT ARM

This 3D model of 2-DOF robot arm was designed by using Solidworks as shown in Fig. 2. Two permanent magnet (PM) DC motors with worm gearbox that are coupled with two encoder were used as the actuator of the robot arm.

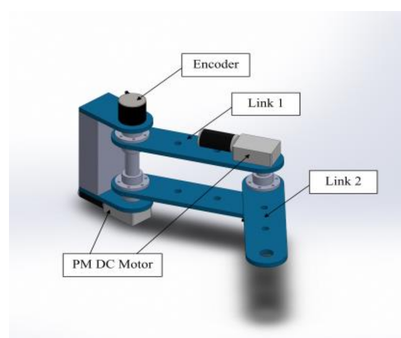

Figure 2. The 3D model of 2-DOF robot arm using Solidworks.

Top view drawing of 2-DOF robot arm is shown in Fig. 3. There are two links and two joints in a 2-DOF robot arm. The joints are driven by two actuators rotating in the x-y plane. The rotational angle of joint 1 and joint 2 are θ_1 and θ_2 within $\pm 90°$ and $150°$ range, respectively. The length of Link 1 and Link 2 are 20 cm, equally.

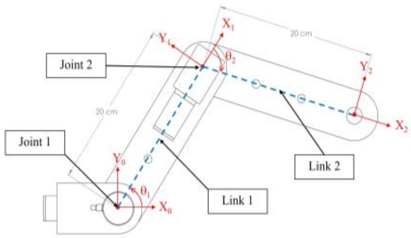

Figure 3. A top view drawing of 2-DOF robot arm.

A. Direct Kinematic Model

In designing a robot arm, kinematic play a vital role. The mathematical tools of spatial descriptions are used in the modeling of robot arm. The kinematic model gives relations between the position and orientation of the end-effector and spatial differential motion that is described in terms of velocity, acceleration and all higher order derivatives of position variables. [1]

To find the kinematic model of 2-DOF robot arm, the transformation matrices which describe coordinate frame 1 with respect to coordinate frame 0 (${}^{0}T_1$) and coordinate frame 2 with respect to coordinate frame 1 (${}^{1}T_2$) must be obtained. The transformation matrices, consisting of rotation around z axis and translation between two frames, are given by

$$ {}^{0}T_1(\theta_1)=\begin{pmatrix} C_1 & -S_1 & 0 & L_1C_1 \\ S_1 & C_1 & 0 & L_1S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{1} $$

$$ {}^{1}T_2(\theta_2)=\begin{pmatrix} C_2 & -S_2 & 0 & L_2C_2 \\ S_2 & C_2 & 0 & L_2S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{2} $$

where $\sin\theta_1=S_1$, $\cos\theta_1=C_1$, $\sin\theta_2=S_2$ and $\cos\theta_2=C_2$.

Therefore, the overall transform matrix of 2-DOF robot arm obtained by combining the individual transform matrices is $T = {}^{0}T_2 = {}^{0}T_1\,{}^{1}T_2$ is given by

$$ T=\begin{pmatrix} C_1C_2-S_1S_2 & -C_1S_2-S_1C_2 & 0 & L_2(C_1C_2-S_1S_2)+L_1C_1 \\ S_1C_2+C_1S_2 & -S_1S_2+C_1C_2 & 0 & L_2(S_1C_2+C_1S_2)+L_1S_1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{3} $$

The overall transform matrix from (3) consist of three unit orientation vectors and one position vector. [3] Focusing on the position vector, the direct kinematic equations of 2-DOF robot arm are given by

$$ d_x = L_2(C_1C_2-S_1S_2)+L_1C_1 \tag{4} $$

$$ d_y = L_2(S_1C_2+C_1S_2)+L_1S_1 \tag{5} $$

B. Inverse Kinematic Model

The direct kinematic model determines the position and orientation of the end-effector for values of joint-link displacement given. In the other words, the inverse kinematics is the determination of a set of position and orientation in Cartesian space that are reachable by the origin of the end-effector frame. [1]

The direct kinematic equations in (4) and (5) can be rearranged to find θ_1 and θ_2. Therefore, the inverse kinematic equations are given by

$$ \theta_1 = A\tan 2\left(\sqrt{1-\left[\frac{d_xC_2+d_yL_2S_2}{d_x^2+d_y^2}\right]^2},\frac{d_xC_2+d_yL_2S_2}{d_x^2+d_y^2}\right) \tag{6} $$

$$ \theta_2 = A\tan 2\left(\sqrt{1-\left[\frac{(d_x^2+d_y^2)-(L_1^2+L_2^2)}{2L_1L_2}\right]^2},\frac{(d_x^2+d_y^2)-(L_1^2+L_2^2)}{2L_1L_2}\right) \tag{7} $$

III. The Design of Control System

This robot arm is controlled by the PM DC motors using PID controller. Feedback control system composes of two encoders coupled with two motors that measure their own angular position and sent back the position as feedback. To tune the proper PID value by using PID controller block in MATLAB-Simulink, model of the actuator system is required.

A. Model of the Actuator System

Fig. 4 shows equivalent circuit of PM DC motor. The DC voltage is applied to the armature winding of the motor. The electrical and mechanical characteristics of the system are represented as follows:

- V_a is the armature voltage (V)
- i_a is the armature current (A)
- R_a is the resistance of winding (Ω)
- L_a is the inductance of winding (H)
- e is the back electromotive force (V)
- K_b is the back electromotive force coefficient (V.s/rad)
- K_t is the motor torque coefficient (N.m/A)
- J is the moment of inertia of the actuator system (kg.m^2)
- b is the viscous friction coefficient of the actuator system (N.m.s/rad)
- ω_m is the motor velocity (rad/s) and
- T_m is the motor torque (N.m). [4]

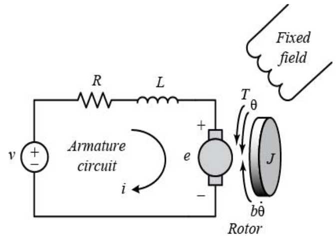

Figure 4. Equivalent circuit of DC motor[5].

The motor equations which are expressed in terms of the Laplace variable S domain are given by (8), (9), (10), and (11). [5]

$$V_a(s) = (L_a s + R_a) I_a(s) + E(s) \tag{8}$$

$$E(s) = K_b \omega_m(s) \tag{9}$$

$$T_m(s) = K_t I_a(s) \tag{10}$$

$$T_m(s) = (Js + b)\omega_m(s) \tag{11}$$

Therefore, block diagram of PM DC motor for estimating parameter of motor is written as shown in Fig. 5.

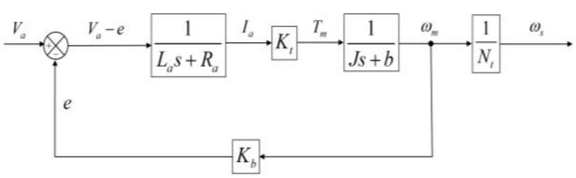

Figure 5. Block diagram of an armature controlled DC motor.

From Fig. 5, N_t is the gear ratio of the worm gearbox and ω_s is velocity of shaft that drives the joint (rad/s). The motor used in this prototype is coupled with worm gearbox with gear ratio 1:100 ($N_t = 100$). Using the multi-meter and LCR meter to measure the resistance and inductance of the motor winding, found that $R_a = 6.5\Omega$ and $L_a = 3.21mH$. Then this value is used as the initial parameter to estimate the values of the other parameters, J , K_b , K_t and b , are based on measuring the motor shaft velocity.

Four parameters of the actuator system resulted from estimation using MATLAB-Simulink based on the simplex search method [6] shown in Fig. 6 are $J = 0.01690 kg.m^2$, $K_b = 1.9452 V.s/rad$, $K_t = 2.2269 kg.m^2/s^2$ and $b = 0.8481 N.m.s/rad$. Therefore, when using all the parameters to run block diagram in Fig. 6, the speed output from block diagram represent a similar trend, compared with measured motor shaft velocity, shown in Fig 7.

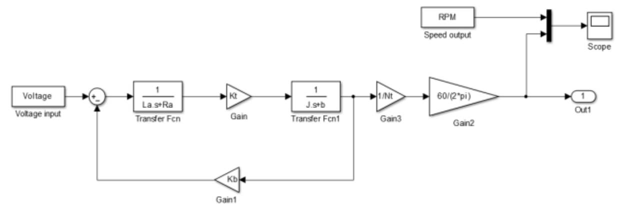

Figure 6. MATLAB-Simulink: Block diagram for parameter estimation.

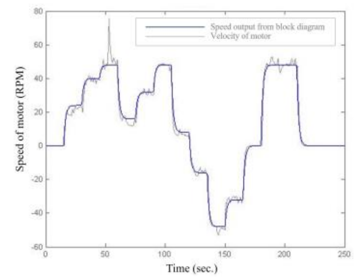

Figure 7. The measured velocity compare with block diagram output.

B. The Motion Control of the Robot Arm

The control system of this robot arm shown as Fig 8 consists of two major system: two feedback control systems of each motors and sub-block of inverse kinematics equations, (6) and (7), that calculate desired position (d_x, d_y) to find angular position of the motors.

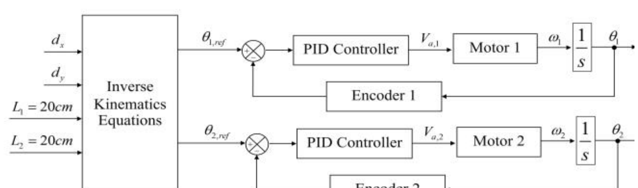

Figure 8. Block diagram control system of this robot arm.

Form Fig. 8, the values, K_p, K_i and K_d , of the PID controller are obtained from Function Block parameter: PID controlled in MATLAB-Simulink as in Fig 9. From tuning, the value include $K_p = 0.0585192$, $K_i = 0.000638936$ and $K_d = 0.0360595$.

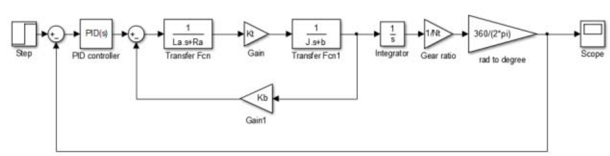

Figure 9. MATLAB-Simulink: Block diagram for PID tuning,

Following this, the values of PID controller derived from tuning are implement in the block diagram to control this robot arm as in Fig 10.

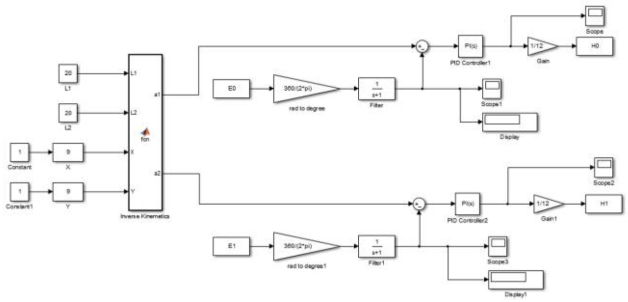

Figure 10. Block diagram for parameter estimation.

IV. THE EXPERIMENTAL RESULTS

A prototype of 2-DOF robot arm is shown in Fig. 11. The robot arm consists of two motors which are coupled with two encoders to measure the angular position and angular velocity of motor and joint. The motors rotate in x-y plane around z-axis.

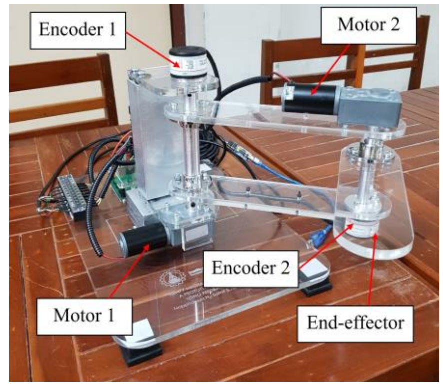

Figure 11. Prototype of 2-DOF robot arm.

The 2-DOF robot arm has been tested by the RAPCON platform [7], [8] with MATLAB-Simulink. The tracking results of motor 1 and motor 2 at different reference input: 15, 45, 60 and 90 degree are shown in Fig. 12 and Fig. 13, respectively.

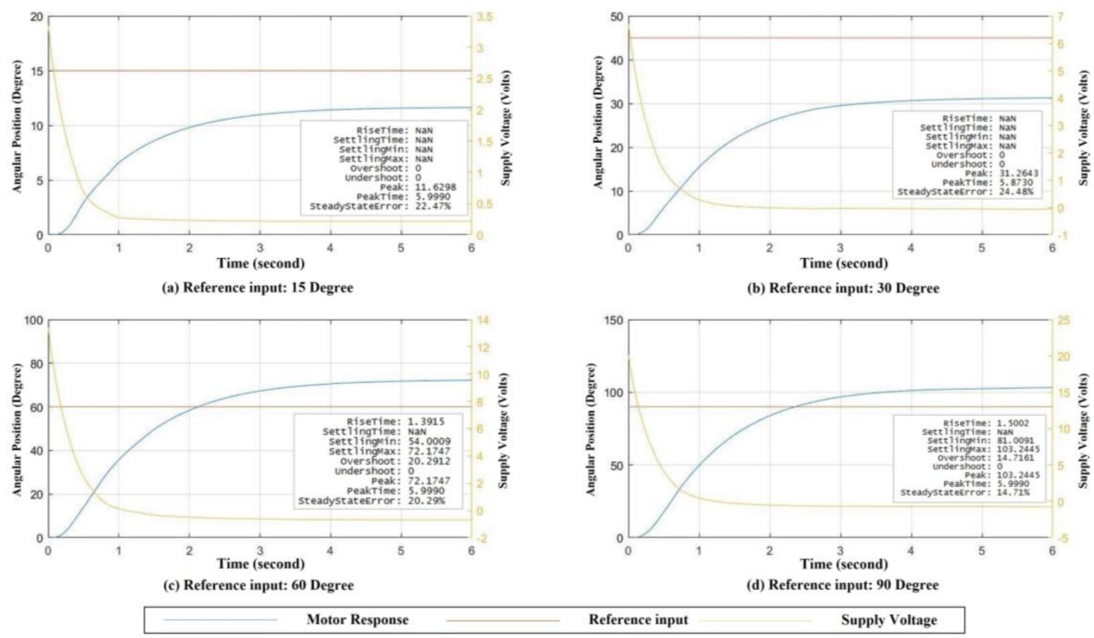

Figure 12. The angular position of Motor 1 at deffirent reference input: (a) 15 degree (a) 30 degree. (a) 60 degree (a) 90 degree.

As reference input were set at higher degree of 60 or 90, Fig. 12(c), Fig. 12(d), Fig. 13(c) and Fig. 13(d) show high reference inputs as 60 or 90 degree. Both motors respond over the reference input with less than 21 degree of maximum overshoots (M_P), rise time (T_r) does not exceed 2 second and steady-state errors (E_{ss}) range from 14% to 21%. In contrast, in Fig. 12(a), Fig. 12(b), Fig. 13(a) and Fig. 13(b) that show the lower reference inputs, 15 or 30 degree, both motors were unable to reach the reference input and had steady-state errors (E_{ss}) range from 20% to 25%.

The errors occurred because of two main factors: the friction of worm gearbox and the control of armature voltage (V_a). From this reason, when step inputs are low, the controller system did not provide enough armature voltage (V_a) to overcome the friction. Meanwhile, in case of high inputs, the controller system is able to provide enough armature voltage (V_a) that can overcome the static friction therefore the motors respond with overshoot but still not enough to pull the arm back to its reference input.

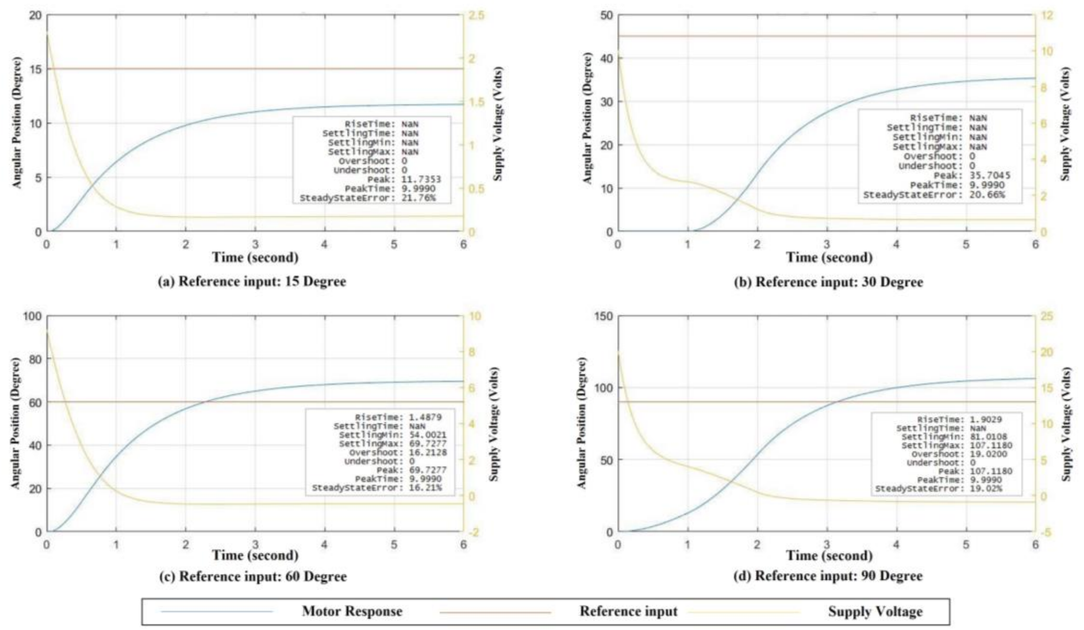

Figure 13. The angular position of Motor 2 at deffirent reference input: (a) 15 degree (a) 30 degree. (a) 60 degree (a) 90 degree.

V. CONCLUSION

This paper present the prototype of 2-DOF robot arm with feedback control system. The motion results of the prototype are step input responses at different reference input. First, at 60 and 90 degree reference input, both motors respond over the reference input with maximum overshoot less than 21 degree of maximum overshoots, rise time does not exceed 2 second and steady-state errors range from 14% to 21%. Second at 15 or 30 degree reference input, both motors were unable to reach the reference input and had steady-state errors range from 20% to 25%. The error occurs because of the friction of worm gearbox and the control of armature voltage.

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