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Estimation of shoulder and elbow joint angle from linear quadratic tracking based on six muscle force vectors

T Herlambang[1], D Rahmalia[2], H Nurhadi[3], A Suryowinoto[4], D F Karya[5]

[1]Department of Information System, Universitas Nahdlatul Ulama Surabaya
[2]Department of Mathematics, Universitas Islam Darul Ulum Lamongan
[3]Department of Mechanical Engineering, Institut Teknologi Sepuluh Nopember
[4]Department of Electrical Engineering, Institut Teknologi Adhi Tama Surabaya
[5]Department of Management, Universitas Nahdlatul Ulama Surabaya

E-mail : teguh@unusa.ac.id, dinitarahmalia@gmail.com

Abstract. Two dimensional human's arm is one of the optimal control application. This arm model consists of joint angles consisting of shoulder joint and elbow joint. Beside that, there are also muscle force vectors consisting of *pectoralis major, posterior deltoid, brachialis, lateral head of triceps brachii, biceps brachii*, and *longhead of triceps*. Linear Quadratic Tracking (LQT) is constructed to obtain solution of state and optimal control. From state solution and optimal control obtained, they will be used estimation by Backpropagation and ANFIS. From data resulted from LQT simulation, the input used are muscle force vectors. They will be used for estimation the output i.e. angle of shoulder joint and angle of elbow joint. From the LQT simulation, the angle position can follow the given reference function. Then Backpropagation and ANFIS can make estimation in angle of shoulder joint and angle of elbow joint based on six muscle force vectors with small RMSE. In Backpropagation, the estimation result of angle of shoulder joint between target and output with RMSE is 0.0954 and the estimation result of angle elbow joint between target and output with RMSE is 0.2528. In ANFIS, the estimation result of angle of shoulder joint between target and output with RMSE is 0.0062 and the estimation result of angle elbow joint between target and output with RMSE is 0.0526.

1. Introduction

Two dimensional human's arm is one of the optimal control application. This arm model consists of joint angles consisting of shoulder joint and elbow joint. Beside that, there are also muscle force vectors consisting of *pectoralis major, posterior deltoid, brachialis, lateral head of triceps brachii, biceps brachii*, and *longhead of triceps*. The muscle force vectors can make the various of angle of shoulder joint and elbow joint [9].

In this research, method used in optimal control is Linear Quadratic Tracking (LQT). From previous research, LQT has been applied in planar arm dynamical model [11] and Kalman Filter has been applied for estimation [10]. But in this research, we develop it with Backpropagation and Adaptive Neuro Fuzzy Inference System (ANFIS). Backpropagation is type of Neural Network used in estimation. Backpropagation consists some inputs, some hidden layers, and some outputs. In Backpropagation, there are three phases of calculation : forward propagation, backward propagation, and update weight matrices [3,7]. While in ANFIS, it consists of five layers and there are forward path for optimization of consequent parameters and backward path for optimimization of premise parameters [1,6].

The basic of LQT is output of the system track or follow a desired trajectory that minimizes a performance index [12]. LQT is constructed to obtain solution of state and optimal control. From state solution and optimal control obtained, they will be used estimation by Backpropagation and ANFIS. From data resulted from LQT simulation, the input used are muscle force vectors. They will be used for estimation the output i.e. angle of shoulder joint and angle of elbow joint. From the LQT simulation, the angle position can follow the given reference function. Then Backpropagation and ANFIS can make estimation in angle of shoulder joint and angle of elbow joint based on six muscle force vectors with small RMSE.

In Backpropagation, the estimation result of angle of shoulder joint between target and output with RMSE is 0.0954 and the estimation result of angle elbow joint between target and output with RMSE is 0.2528. In ANFIS, the estimation result of angle of shoulder joint between target and output with RMSE is 0.0062 and the estimation result of angle elbow joint between target and output with RMSE is 0.0526.

2. Construction of state space model

Figure 1 shows the diagram of two dimensional human's arm, in which there are two main joints i.e. shoulder joint with the subscript 1 and elbow joint with the subscript 2. For moving the angle position of human's arm, there are also muscles namely *pectoralis major, posterior deltoid, brachialis, lateral head of triceps brachii, biceps brachii,* and *longhead of triceps*. When the six muscles give the force, then the human's arm can change the angle position and occur the change of shoulder and elbow joint angle.

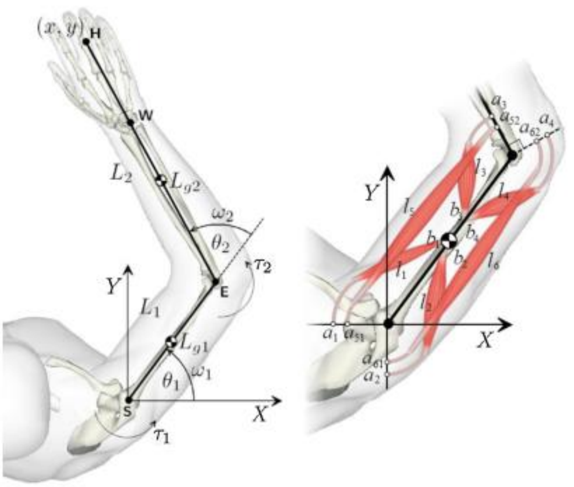


Figure 1. Two dimensional human's arm.

We note joint angles consisting of shoulder joint and elbow joint as $\theta = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}$ respectively, angle velocities derived from the change of angle $\dot{\theta} = \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} \omega_1 \\ \omega_2 \end{bmatrix}$ respectively, and joint torquest of muscle forces $\tau_{muscle} = \begin{bmatrix} \tau_{1,muscle} \\ \tau_{2,muscle} \end{bmatrix}$. Therefore, equation (1) can be constructed as dynamical model of human's arm model.

$$\begin{bmatrix} \alpha+2\beta\cos\theta_2 & \delta+\beta\cos\theta_2 \\ \delta+\beta\cos\theta_2 & \delta \end{bmatrix}\begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix}+\begin{bmatrix} -\beta\dot{\theta}_2\sin\theta_2 & -\beta(\dot{\theta}_1+\dot{\theta}_2)\sin\theta_2 \\ \beta\dot{\theta}_1\sin\theta_2 & 0 \end{bmatrix}\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}+\begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}=\tau_{muscle} \quad (1)$$

With $\alpha = I_1 + I_2 + m_1L_{g1}^2 + m_2(L_1^2 + L_{g2}^2)$, $\beta = m_2L_1L_{g2}$, $\delta = I_2 + m_2L_{g2}^2$

L_1, L_2 are the length of shoulder and elbow joint respectively, m_1, m_2 are the mass of shoulder and elbow joint respectively, L_{g1}, L_{g2} are mass center of shoulder and elbow joint respectively, I_1, I_2 are inertia moment of shoulder and elbow joint.
In the right side, there are six muscles vectors as control in the system in equation (2) :

$$\tau_{muscle} = W^T U = \begin{bmatrix} -a_1 & a_2 & 0 & 0 & -a_{51} & a_{61} \\ 0 & 0 & -a_3 & a_4 & -a_{52} & a_{62} \end{bmatrix}\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \\ U_6 \end{bmatrix} \quad (2)$$

Where $U_1, U_2, U_3, U_4, U_5, U_6$ are muscle force vectors *pectoralis major, posterior deltoid, brachialis, lateral head of triceps brachii, biceps brachii,* and *longhead of triceps* respectively.

Substitute $\theta = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}$, $\dot{\theta} = \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} \omega_1 \\ \omega_2 \end{bmatrix}$, $\ddot{\theta} = \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} = \begin{bmatrix} \dot{\omega}_1 \\ \dot{\omega}_2 \end{bmatrix}$, so that the dimension of matrices in the equation (1) are augmented :

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \alpha+2\beta\cos\theta_2 & \delta+\beta\cos\theta_2 \\ 0 & 0 & \delta+\beta\cos\theta_2 & \delta \end{bmatrix}\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\omega}_1 \\ \dot{\omega}_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & \beta\omega_2\sin\theta_2 - b_{11} & \beta(\omega_1+\omega_2)\sin\theta_2 - b_{12} \\ 0 & 0 & -\beta\omega_1\sin\theta_2 - b_{21} & -b_{22} \end{bmatrix}\begin{bmatrix} \theta_1 \\ \theta_2 \\ \omega_1 \\ \omega_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -a_1 & a_2 & 0 & 0 & -a_{51} & a_{61} \\ 0 & 0 & -a_3 & a_4 & -a_{52} & a_{62} \end{bmatrix}\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \\ U_6 \end{bmatrix} \quad (3)$$

3. Discrete Linear Quadratic Tracking (LQT)

Linear Quadratic Tracking (LQT) can be applied in order that the system can track the given trajectory r with the minimum performance index J. In this research, LQT is solved by discrete time [2],[5] :

Suppose that state equation $\dot{x}(t)$ and output $y(t)$ are in equation (4) and (5) respectively.

$$x_{k+1} = Ax_k + Bu_k \quad (4)$$

$$y_k = Cx_k \quad (5)$$

and the Performance Index is :

$$J = \frac{1}{2}e_N^T P e_N + \frac{1}{2}\sum_{k=0}^{N-1}\left(e_k^T Q e_k + u_k^T R u_k\right) \quad (6)$$

with $e_N = Cx_N - r_N$ and $e_k = Cx_k - r_k$

and matrices $P \geq 0$, $Q \geq 0$ and $R > 0$

1. Calculate K_k, S_k, v_k, K_k^v with final conditions $S_N = C^T PC$ and $v_N = C^T Pr_N$

$$K_k = (B^T S_{k+1} B + R)^{-1} B^T S_{k+1} A \tag{7}$$
$$S_k = C^T QC + A^T S_{k+1}(A - BK_k) \tag{8}$$
$$v_k = (A - BK_k)^T v_{k+1} + C^T Qr_k \tag{9}$$
$$K_k^v = (B^T S_{k+1} B + R)^{-1} B^T \tag{10}$$

2. Calculate x_k with initial conditions x_0

$$x_{k+1} = Ax_k + B(-K_k x_k + K_k^v v_{k+1}) \tag{11}$$

3. Calculate optimal control u_k

$$u_k = -K_k x_k + K_k^v v_{k+1} \tag{12}$$

4. Estimation method
Estimation method used in this research are Backpropagation and Adaptive Neuro Fuzzy Inference System (ANFIS). Before Backpropagation and ANFIS are applied, we need to determine input and output variables as in Figure 2 [4]. From data resulted from LQT simulation, the input used are six muscle force vectors consisting of *pectoralis major* U_1, *posterior deltoid* U_2, *brachialis* U_3, *triceps brachii (lateral head)* U_4, *biceps brachii* U_5, and *triceps (longhead)* U_6. They will be used for estimation the output i.e. angle of shoulder joint θ_1 and angle of elbow joint θ_2.

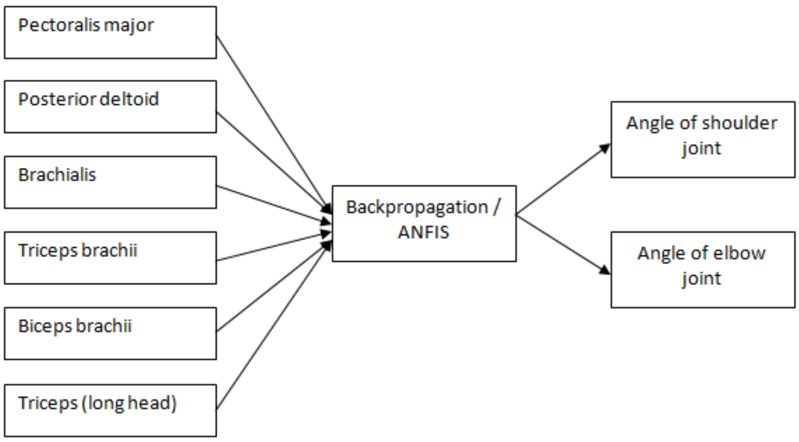


Figure 2. Input dan output variables used in estimation using Backpropagation and ANFIS.

4.1. Backpropagation
Backpropagation of neural network can be used for estimation. It has inputs $x_1, x_2, ..., x_n$, hidden layers $z_1, z_2, ..., z_p$, and outputs $y_1, y_2, ..., y_m$ like in figure 3. In Backpropagation, there are three phases of calculation such as forward propagation from input to output with linear combination of each node value, backward propagation from output to input with carrying error between target and output, and update weight matrices for producing better estimation [13].

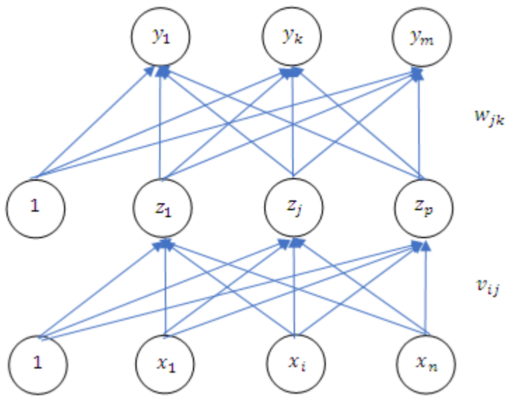


Figure 3. Backpropagation structure.

4.2. Adaptive Neuro Fuzzy Inference System (ANFIS)

Adaptive Neuro Fuzzy Inference System (ANFIS) is the development of fuzzy system with the neural network. Figure 4 shows the diagram of Adaptive Neuro Fuzy Inference System (ANFIS) which consists of five layers and there are forward path for optimization of consequent parameters and backward path for optimimization of premise parameters. The algorithm for each layer can be seen in Table 1 [8].

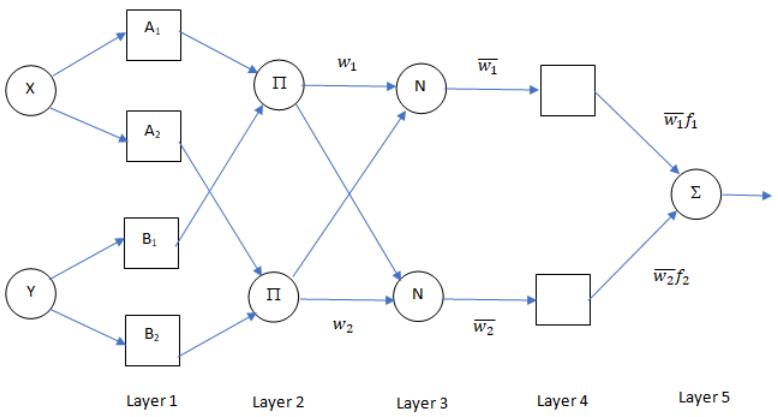


Figure 4. ANFIS structure.

Table 1. ANFIS algorithm for each layer.

Layer	**Computation**
1	$O_{1,i} = \mu_{Ai}(x)$ $i=1,2$, $O_{1,i} = \mu_{Bi-2}(y)$ $i=3,4$
2	$O_{2i} = w_i = \mu_{Ai}(x) * \mu_{Bi}(y)$ $i=1,2$
3	$O_{3i} = \overline{w_i} = \dfrac{w_i}{\sum_i w_i}$ $i=1,2$
4	$O_{4i} = \overline{w_i} f_i = \overline{w_i}(p_i x + q_i y + r_i)$ $i=1,2$
5	$O_5 = \sum_i \overline{w_i} f_i$

5. Results

This part will explain about LQT simulation for determining input, i.e. optimal control *pectoralis major* U_1, *posterior deltoid* U_2, *brachialis* U_3, *triceps brachii (lateral head)* U_4, *biceps brachii* U_5, and *triceps (longhead)* U_6 and output angle of shoulder joint θ_1 and angle of elbow joint θ_2. From state solution and optimal control obtained, they will be used estimation by Backpropagation and ANFIS.

5.1. LQT Simulation

The parameters used in two dimensional human's arm model can be seen in table 2 [9].

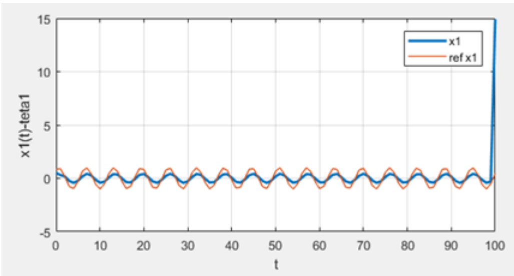
Table 2. Parameters of two dimensional human's arm model.

Parameters	Shoulder joint (*i=1*)	Elbow joint (*i=2*)
Length (m) (L_i)	0.298	0.419
Mass (kg) (m_i)	2.089	1.912
Mass center (m) (L_{gi})	0.152	0.181
Inertia moment (kg m^2) (I_i)	0.0159	0.0257

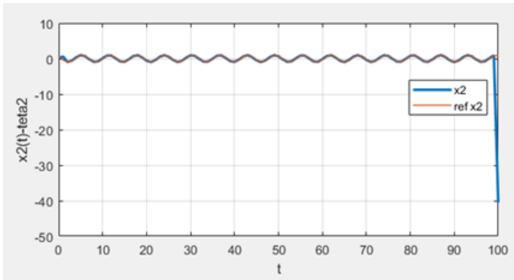
With the moment lever matrix (in meter) are [9]:

$$a_1 = a_2 = 0.055 \quad a_3 = a_4 = 0.045 \quad a_{51} = 0.055 \quad a_{52} = 0.045 \quad a_{61} = 0.055 \quad a_{62} = 0.045$$

When discrete Linear Quadratic Tracking (LQT) is applied with tracking reference are $ref(\theta_1) = \sin(t)$, $ref(\theta_2) = \cos(t)$, the numerical solution of angle of shoulder joint and angle of elbow joint can be seen in figure 5(a) and figure 5(b) respectively. From the simulation, the angle position can follow the given reference function.



(a)



(b)

Figure 5. Numerical solution result (a) Angle of shoulder joint (b) Angle of elbow joint.

Figure 6 shows the results of *pectoralis major* U_1, *posterior deltoid* U_2, *brachialis* U_3, *triceps brachii (lateral head)* U_4, *biceps brachii* U_5, and *triceps (longhead)* U_6 as optimal controls from muscle force vectors (in Newton). Because the tracking reference are $ref(\theta_1) = \sin(t)$, $ref(\theta_2) = \cos(t)$, then the controls have fluctuative pattern.

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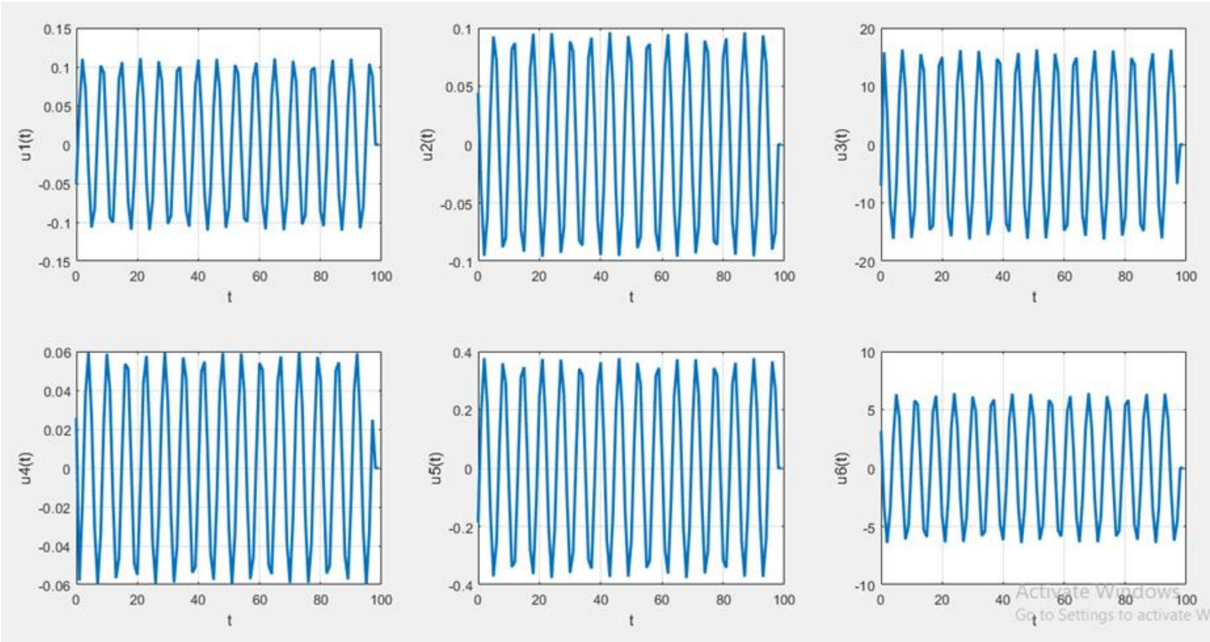
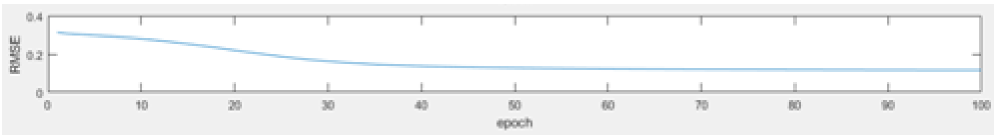


Figure 6. Six optimal controls from six muscle force vectors.

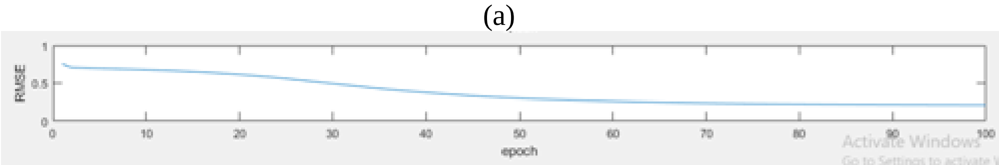
From state solution and optimal control obtained, they will be used estimation by Backpropagation and ANFIS. From data resulted from LQT simulation, the input used are six muscle force vectors They will be used for estimation the output i.e. angle of shoulder joint θ_1 and angle of elbow joint θ_2.

5.2. Backpropagation estimation

Before Backpropagation algorithm is applied, we divide the dataset into training data (80%) and testing data (20%). Then we normalize the data so that the range of dataset are 0-1. When Backpropagation is applied in training data until 100 epoch, the data are de-normalized so that the value are original and the root of mean square error (RMSE) decrease like in figure 7(a) and figure 7(b). Figure 7(a) is traning process of angle of shoulder joint with RMSE is 0.116 and figure 7(b) is training process of angle elbow joint with RMSE is 0.2114.



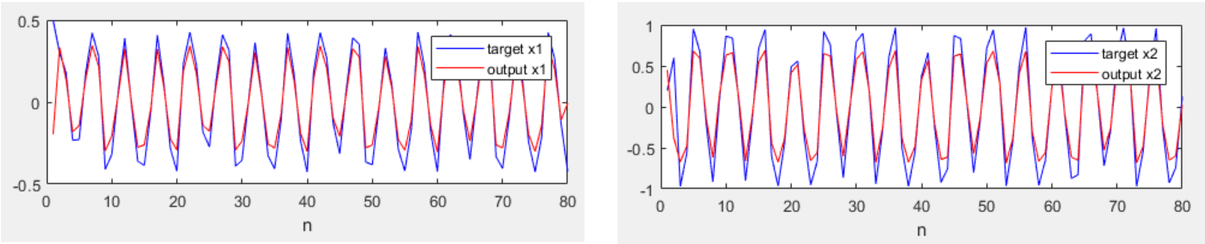
(a)



(b)

Figure 7. Training process (a) angle of shoulder joint (b) angle of elbow joint.

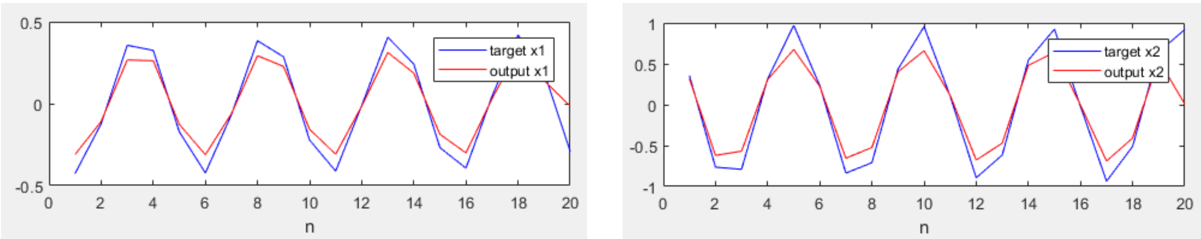
The estimation result of training data can be seen in figure 8(a) and figure 8(b). Figure 8(a) is estimation result of angle of shoulder joint between target and output and figure 8(b) is estimation result of angle elbow joint between target and output.



(a) (b)

Figure 8. Estimation result of training data (a) Angle of shoulder joint (b) Angle of elbow joint.

The optimal weight matrices obtained from training process are applied in testing data. The estimation result of testing data can be seen in figure 9(a) and figure 9(b). Figure 9(a) is estimation result of angle of shoulder joint between target and output with RMSE is 0.0954 and figure 9(b) is estimation result of angle elbow joint between target and output with RMSE is 0.2528.

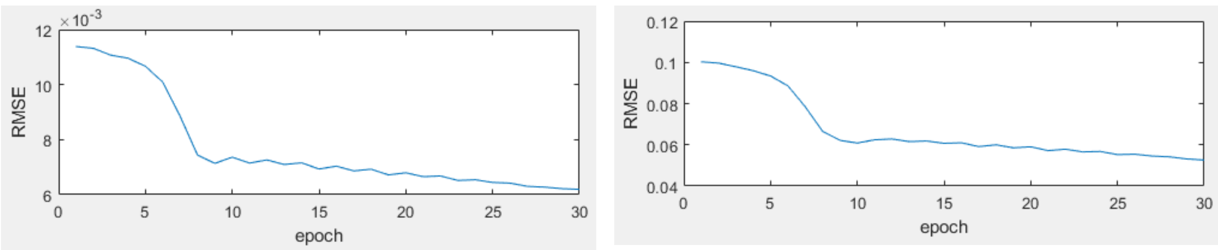


(a) (b)

Figure 9. Estimation result of testing data (a) Angle of shoulder joint (b) Angle of elbow joint.

5.3. ANFIS estimation

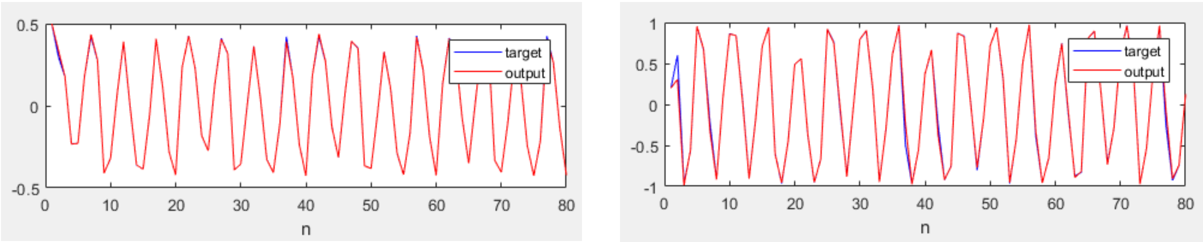
In ANFIS estimation, we also divide the dataset into training data (80%) and testing data (20%) like in Backpropagation. In ANFIS, we only train the dataset until 30 epoch and the root of mean square error (RMSE) decrease like in figure 10(a) and figure 10(b). Figure 10(a) is traning process of angle of shoulder joint with RMSE is 0.0062 and figure 10(b) is training process of angle elbow joint with RMSE is 0.0526.



(a) (b)

Figure 10. Training process (a) angle of shoulder joint (b) angle of elbow joint.

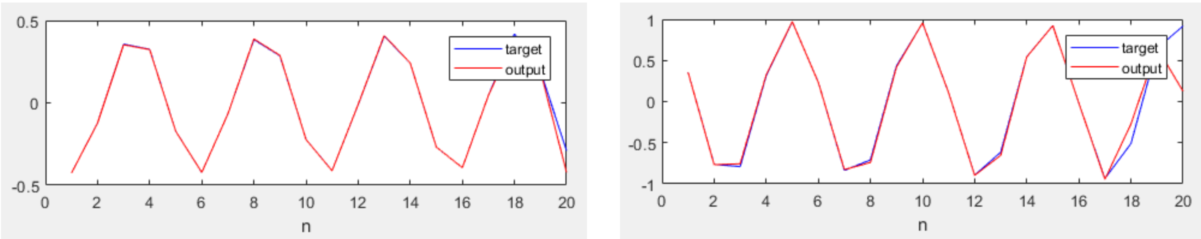
The estimation result of training data can be seen in figure 11(a) and figure 11(b). Figure 11(a) is estimation result of angle of shoulder joint between target and output and figure 11(b) is estimation result of angle elbow joint between target and output.



(a) (b)

Figure 11. Estimation result of training data (a) Angle of shoulder joint (b) Angle of elbow joint.

The optimal ANFIS parameters obtained from training process are applied in testing data. The estimation result of testing data can be seen in figure 12(a) and figure 12(b). Figure 12(a) is estimation result of angle of shoulder joint between target and output with RMSE is 0.0301 and figure 12(b) is estimation result of angle elbow joint between target and output with RMSE is 0.1859.



(a) (b)

Figure 12. Estimation result of testing data (a) Angle of shoulder joint (b) Angle of elbow joint.

6. Conclusions

There are two main joints in human's arm model i.e. shoulder joint and elbow joint. For moving the position of human's arm, there are also muscles consisting of *pectoralis major, posterior deltoid, brachialis, lateral head of triceps brachii, biceps brachii*, and *longhead of triceps*. Linear Quadratic Tracking (LQT) is constructed to obtain solution of state and optimal control. From state solution and optimal control obtained, they will be used estimation by Backpropagation and ANFIS. From data resulted from LQT simulation, the input used are six muscle force vectors. They will be used for estimation the output i.e. angle of shoulder joint and angle of elbow joint. From the LQT simulation, the angle position can follow the given reference function. Then Backpropagation and ANFIS can make estimation in angle of shoulder joint and angle of elbow joint based on six muscle force vectors with small RMSE.

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