Al-Nahrain Journal for Engineering Sciences (NJES) Vol.20 No.4, 2017 pp.853-863

Adaptive Control of Robot Manipulators with Velocity Estimation and Bounded Torque

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Abstract
The robot manipulator output feedback problem points out to the controlled system in which the measurements of the joint position are available. In this study, all kinematic and dynamic parameters of robot manipulator are supposed unknown and the manipulator have to follow the desired trajectory. Therefore, the adaptive control problem for robot manipulators based on velocity estimation is investigated. According to the practical robot actuator power limitation, the bounded torque input is also considered in this study. The control algorithm is applied for 2-link manipulator to evaluate controller effectiveness. The design parameters that guaranteed the control performance of closed loop system are chosen by using optimization output constrained method. The proposed controller performances are provided by numerical simulations.
Keywords: Adaptive control, velocity estimation, bounded torque, kinematic parameters, robot manipulators, performance.

1. Introduction
Adaptive control of robot arms based on of tracking controller–observer schemes has been dealt in great detail in the literature. So far, however, there has been little discussion about adaptive output feedback tracking (OFT) controllers for manipulators of robot, as discussed in literatures [1-4]. In addition, the study on the adaptive control of robot manipulators with dynamic parameter uncertainty has a long and rich history (see, e.g., the early results in [5], [6], [7]), and the employment of adaptive control provides robot manipulators with the ability of performing tasks in the unknown environment. Recently, researchers have shown an increased interest in adaptive robot control as in [8], [9], [10], [11] aiming at handling the kinematic parameter uncertainty.
Recent developments in the field of adaptive controlling have led to a renewed interest the problem of output feedback (OFB) link position tracking control of robot. Cho et al. [12] studied the adaptive time-delay control (TDC) with a supervising switching technique (SST) for controlling robot manipulators. TDC was enhanced by using two adaptive techniques .The gain of the controller was tuned by adaptive method in which a class of Nussbaum functions were applied. Also, by using constant gain, the results of these functions were compared with conventional TDC. The controlling method was used to deal with inertia parameter variations that come from robot manipulator movement. The discontinuous disturbances were treated by using the supervising switching technique (SST). The approach showed highly accurate, robust and model free. He et al. [13] developed impedance control supported by neural networks to settle the difficulties arise in robot manipulator issues. Two types of controller were implemented, full states and output feedback controllers. In addition, an auxiliary signal was used to handle the effect of saturation for the manipulator. The results showed that the proposed controller was very efficient to track a desired model with satisfactory performance. In addition, Zavala-Río et al. [14] designed PID type controller based on output feedback for the global stabilization of manipulators with bounded inputs. The structure of SPD-PI was used by maintaining P and D effects together within a generalized saturation function while considering an additional similar saturation I effect individually. Furthermore, experimental test was conducted for 2nddegree of freedom manipulator to verify and enhance the results obtained for the proposed controller design. Li et al. [15] studied the adaptive output feedback controller using fuzzy logic approach to control single link manipulator integrated with DC brushed motor. The main purpose of that controller was compensating the nonlinear dynamics associated with the mechanical subsystem and the electrical subsystems while only requiring the measurements of link position. The fuzzy logic approach was used to approximate the unknown nonlinearities while adaptive fuzzy filter observer was used to estimate the states that could not measured. The Lyapunov direct method was implemented to ensure and proof the stability of controlled system. The proposed design approach exhibited three key advantages: (i) the controller did not require all the states of the system be measured directly, (ii) the problem of robotic manipulators with unknown nonlinear uncertainties could be solved with this proposed controller, and (iii) the complexity was avoided. Also, Su and Zheng [16] studied the asymptotic regulation problem of

robot manipulators. A vision-based feedback and position measurements were only available. PID controller supported by simple image-based output feedback transpose Jacobian was designed. The closed loop system stability was verified by using both LaSalle's invariance theorem and Lyapunov's direct method. A manipulator of 2nd DOF was used in the simulation which showed the significant of the proposed controller. A little far, Belanger [17] provided the importance of implementing control design approaches to avoid the need for measurements of velocity. Kalman filter was used to estimate the angular velocities. He showed great improvement when using a Kalman filter against the specialized method such as numerical integration of the position measurements.

In many applications of robots, the joint velocity is estimated from position measurements rather than from velocity sensors such as tachometer, which may provide signals with noise. In addition, the actuators of robots have one main disadvantage that represented by physical constraints, which the amplitude of the available torques is limited. Possible problems that could result from the implementation of controllers based on the unlimited available torque assumption include degraded link position tracking and thermal or mechanical failure. Therefore, when designing control strategies for such mechanisms, it is important to take into account those actuator limits.

According to the literature survey that the design of such output feedback controllers, which torque inputs are bounded, has been targeted at the set-point control. From the previous work, it known that the researchers have less attention regarding the general tracking control problem. In this paper, proposed a design of an adaptive controller with proper parameter estimation update law in which the error between the time varying actual position and desired position of the robot manipulator system converges asymptotically to zero. To obtain this goal, the adaptive controller adopted only the position measurement of joint, estimates the velocity and produces a saturated torque input. With this controller, the local exponential stability for closed loop system is guaranteed.

Notation: Everywhere this article we use the following notations

Symbols	Definition
$\|\|x\|\| = \sqrt{x^T x}$	the norm of vector $x \in \mathbb{R}^n$
$\lambda_{min}\{A(x)\}$	the minimum eigenvalues of a symmetric positive definite matrix $A(x) \in \mathbb{R}^{n\times n}$ for all $x \in \mathbb{R}^n$
$\lambda_{max}\{A(x)\}$	the maximum eigenvalues of a symmetric positive definite matrix $A(x) \in \mathbb{R}^{n\times n}$ for all $x \in \mathbb{R}^n$
$\|\|B(x)\|\| = \sqrt{\lambda_{max} B(x)^T B(x)}$	the induced norm of a matrix $B(x) \in \mathbb{R}^{n\times n}$ for all $x \in \mathbb{R}^n$
$\mathrm{hypfunc}(x)$	the hyperbolic function of $x \in \mathbb{R}$

2. Robot manipulator model and properties

The system model for an n-rigid link, revolute, direct-drive robot is assumed to be of the following form [18]:

$$M(q)\ddot{q} + V_m(q,\dot{q})\dot{q} + G(q) + F_d\dot{q} = \tau \qquad (1)$$

where $q, \dot{q}, \ddot{q} \in \mathbb{R}^n$ denote the link position, velocity, and acceleration vectors, respectively, $M(q) \in \mathbb{R}^{n\times n}$represents the link inertia matrix, $V_m(q,\dot{q}) \in \mathbb{R}^{n\times n}$ represents centripetal-Coriolis matrix, $G(q) \in \mathbb{R}^{n\times 1}$ represents the gravity effects, $F_d \in \mathbb{R}^{n\times n}$ is the constant, diagonal positive-definite, viscous friction coefficient matrix, and $\tau \in \mathbb{R}^n$denotes the vector of torque input. The main assumption of this work is that the displacements of robot joint are available for measurements and the uncertainties of robot parameters are present. Thereafter, the aim of the proposed control scheme is to propose a controller in which both of control input,τ, and parameter estimation update law are pushing the joint displacements $q(t) \in \mathbb{R}^n$for converging asymptotically to joint displacements $q_d(t) \in \mathbb{R}^n$ which are desired earlier, i.e.,

$$\lim_{t\to\infty} e(t) = 0 \qquad (2)$$

where

$e(t) = q_d(t) - q(t)$ denotes the tracking error.

Everywhere this article, the desired joint displacement, $q_d(t)$is considered three times differentiable and

$$\|\dot{q}_d(t)\| \leq \|\dot{q}_d\|_M \quad \forall\, t \geq 0, \qquad (3)$$

$$\|\ddot{q}_d(t)\| \leq \|\ddot{q}_d\|_M \quad \forall\, t \geq 0, \qquad (4)$$

where $\|\dot{q}_d\|_M > 0$ and $\|\ddot{q}_d\|_M > 0$are define as known constants.

The dynamic model of equation (1) has the following properties which adopted in the analysis of current proposed controller [18-21]:

Property 1: The inertia matrix $M(q)$ is symmetric and uniformly positive definite.

Property 2 : As all $q, \dot{q}, \ddot{q} \in \mathbb{R}^n$, then the dynamic model (1) will become

$M(q)\ddot{q} + V_m(q,\dot{q})\dot{q} + G(q) + F_d\dot{q} = Y(q,\dot{q},\ddot{q})\theta$

where $Y(q,\dot{q},\ddot{q}) \in \mathbb{R}^{n\times r}$ is the dynamic regressor matrix and $\theta \in \mathbb{R}^r$ is the constant parameter vector consisting from two parameters which are payload and robot parameters.

Property 3 : For all $q, \dot{q}, x, y, z \in \mathbb{R}^n$, the inertia and Coriolis matrix satisfy

$$\lambda_{max}\{M(q)\}\|x\|^2 \geq x^T M(q) x \geq \lambda_{min}\{M(q)\}\|x\|^2, \quad (5)$$

$$\dot{M}(q) = V_m(q,\dot{q}) + V_m(q,\dot{q})^T, \quad (6)$$

$$V_m(x,y)z = V_m(x,z)y$$

$$V_m(x,y+z) = V_m(x,y) + V_m(x,z)$$

$$\|V_m(q,\dot{q})\| \leq k_{C1}\|\dot{q}\|, \quad (7)$$

$$x^T\left[\frac{1}{2}\dot{M}(q) - V_m(q,\dot{q})\right]x = 0.$$

Property 4: The following residual dynamics [22], [23]:

$$\begin{aligned} res(e,\dot{e}) =& [M(q_d) - M(q)]\ddot{q}_d + [V_m(q_d,\dot{q}_d) - \\ & V_m(q,\dot{q})]\dot{q}_d + [G(q_d) - G(q)], \end{aligned} \quad (8)$$

obeys the following inequality Equation [10];

$$\|res(e,\dot{e})\| \leq c_1\|\dot{e}\| + \frac{\delta\alpha}{\tanh(\alpha\sigma)}\|\tanh(\sigma e)\|. \quad (9)$$

Where σ is defined as a strictly positive constant,

$c_1 = k_{V_m1}\|\dot{q}_d\|_M$,

$\delta = k_G + k_M\|\dot{q}_d\|_M + k_{V_m2} + k_M\|\dot{q}_d\|_M^2$

$\alpha = 2\dfrac{k_1 + k_2\|\ddot{q}_d\|_M + k_{V_m1}\|\dot{q}_d\|_M^2}{\delta}$.

The references [24] and [25] define the constants involved in the robot model properties.

3. Design of Adaptive controller

In this section, based on references [2] and [3], an adaptive controlling design is proposed to control the manipulator of robot. First, by considering the control law and second, by analysing the parameters estimation update law. Figure1 depicts the adaptive OFT controller in block diagram form.

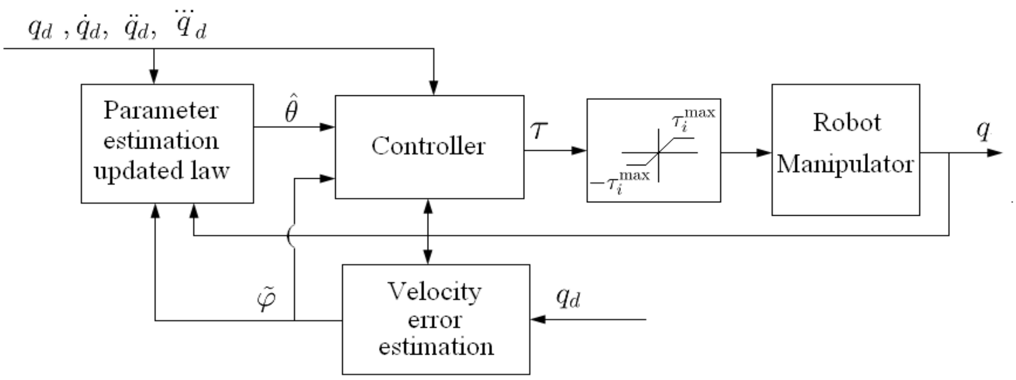

Figure 1: Block diagram for controlling scheme which proposed in the current work.

For designing adaptive controller, let propose the following control law

$$\begin{aligned} \tau =& Y(q_d,\dot{q}_d,\ddot{q}_d)\hat{\theta} + K_v\tanh(\tilde{\varphi}) \\ & + K_p\tanh(\sigma e) \end{aligned} \quad (10)$$

where

$K_v = \text{daig}\{k_{v1},\cdots,k_{vn}\}$ and

$K_p = \text{daig}\{k_{p1},\cdots,k_{pn}\}$,

are positive definite matrices, $\hat{\theta} \in \mathbb{R}^r$ is the estimated parameter vector provided by update law, σ is a constant (strictly positive) and $\tilde{\varphi}$ is calculated from the below nonlinear filter

$$\dot{x} = A\tanh(\tilde{\varphi}), \quad (11)$$

$$\tilde{\varphi} = x + Be \quad (12)$$

where

$A = \text{daig}\{a_1,\cdots,a_{vn}\}$ and $B = \text{daig}\{b_1,\cdots,b_{pn}\}$ are positive definite matrices.

For analysis of adaptive controller, let the parameters estimation update law of robot calculated from the following

$$\begin{aligned} \hat{\theta} =& \Gamma\left[Y^T(q_d,\dot{q}_d,\ddot{q}_d)e - \int_0^t \left\{\dot{Y}^T(q_d\dot{q}_d,\ddot{q}_d)e\right.\right. \\ & \left.\left. -\xi Y^T(q_d,\dot{q}_d,\ddot{q}_d)\tanh(\sigma e)\right\}dt\right. \end{aligned} \quad (13)$$

where Γ is a positive definite matrix and $\xi \in (\xi_{min},\xi_{max})$ the strictly positive constant.

For forming closed loop system, the control law given in (10) is substituted in the dynamic equation of robots given in (1).The parameter estimation error is defined as

$$\tilde{\theta} = \theta - \hat{\theta} \in \mathbb{R}^r \quad (14)$$

And by using property 1, the differentiating of equation (12) w.r.t. time becomes;

$$\frac{d}{dt}\begin{bmatrix} e \\ \dot{e} \\ \\ \\ \tilde{\vartheta} \\ \tilde{\theta} \\ \\ \\ \end{bmatrix} = \begin{bmatrix} \dot{e} \\ M(q)^{-1}[-V_m(q,\dot{q}) - F_d\dot{e} \\ -K_v\tanh(\tilde{\vartheta}) - K_p\tanh(\sigma e) \\ -res(e,\dot{e}) + Y(q_d,\dot{q}_d,\ddot{q}_d)\tilde{\theta}] \\ -A\tanh(\tilde{\vartheta}) + B\dot{e} \\ \Gamma\left[-Y^T(q_d,\dot{q}_d,\ddot{q}_d)\dot{e} + \right. \\ \xi Y^T(q_d,\dot{q}_d,\ddot{q}_d) \\ [\tanh(\vartheta) - \tanh(\sigma e)] \end{bmatrix} \quad (15)$$

4. Control Inputs Constrains

Practically, the control input of the robot manipulator is constrained according to actuator properties and let that constrains obey the following formula;

$$|\tau_i| \leq \tau_i^{max} \quad , i = 1, \cdots, n, \tag{16}$$

where

$$\tau_i^{max} > \sup_{\forall\ q \in \mathbb{R}^n} G_i(q)$$

Moreover, the estimated parameters vector $\hat{\theta}(t)$is bounded for all time that is mean

$$\left\|\hat{\theta}(t)\right\| \leq \left\|\hat{\theta}\right\|_M \qquad \forall\ t \geq 0 \tag{17}$$

Then, the inequality

$$\sup_{\forall t \geq 0} \{\| Y_i(q_d(t), \dot{q}_d(t), \ddot{q}_d(t)) \| |\hat{\theta}||_M + k_{vi} + k_{pi} < \tau_i^{max} \tag{18}$$

Where $Y_i \in \mathbb{R}^r$ is defined as $i - \text{row}$ of the regression matrix $Y_i \in \mathbb{R}^{n \times r}$calculated through the desired trajectory $q_d(t)$ in which the control input (10) remains into the torque space (16).

According to the vector of parameter estimation error $\tilde{\theta}(t)$ which remains bounded, defining the constant

$$\theta_i^{max} \geq \theta_i \quad \text{where} \quad i = \{1, \cdots, r\},$$

where θ_i^{max} is defined as a upper bound of the real parameters of robot, θ_i, and let assume the initial conditions to be: $e(0) = \dot{e}(0) = \tilde{\vartheta}(0) = 0$. Then it is possible to demonstrate that

$$||\hat{\theta}||_M \leq \sqrt{\frac{\lambda_{max}\{\Gamma^{-1}\}}{\lambda_{min}\{\Gamma^{-1}\}}} \left[||\theta^{max} - \hat{\theta}(0)|| + ||\theta^{max}||\right].$$

5. Stability

Benefiting from what presented in references [3,5, 6, 7], the system of closed loop given in (15) is globally stable in the Lyapunov direct method (sense) for some domain belonging to the three dimensional space. For proving stability, the following assumptions are considered:

$$\lambda_{min}\{k_p\} > \gamma_1 \quad \text{and} \quad \xi_{min} < \xi < \xi_{max} \tag{19}$$

The ξ_{min} and ξ_{max} are constant and can calculated as below

$$\xi_{min} = \max\{\xi_1, \xi_2\}$$
$$\xi_{max} = \min\{\xi_3, \xi_4, \xi_5, \xi_6\}$$

where

$$\xi_1 = \frac{2}{\sqrt{\lambda_{min}\{k_p\} - \gamma_1}} \cdot \frac{\gamma_1}{\sqrt{\lambda_{min}\{M_(q)\}\lambda_{min}\{B\}\operatorname{sech}^2(d) - 4\gamma_6}},$$

$$\xi_2 = \frac{4|\lambda_{min}\{F_d\} - c_1|}{\lambda_{min}\{M_{(q)}\}\lambda_{min}\{B\}\operatorname{sech}^2(d) - 4\gamma_2^2},$$

$$\xi_3 = \frac{[\lambda_{min}\{k_p\} - \gamma_1]\lambda_{min}\{k_v B^{-1} A\}}{[\lambda_{min}\{k_p\} - \gamma_1]\lambda_{max}\{k_v\} + \gamma_4^2},$$

$$\xi_4 = \frac{\lambda_{min}\{M(q)\}\lambda_{min}}{\lambda_{min}\{M(q)\}\lambda_{min}} \cdot \frac{\{B\}\operatorname{sech}^2(d)\lambda_{min}\{k_v B^{-1} A\}}{\{B\}\operatorname{sech}^2(d)\lambda_{min}\{k_v\} + \gamma_5^2},,$$

$$\xi_5 = \frac{\sqrt{\sigma^{-1}\lambda_{min}\{k_p\}\lambda_{min}\{M(q)\}/2}}{\lambda_{max}\{M(q)\}},$$

$$\xi_6 = \frac{\sqrt{\lambda_{min}\{k_v B^{-1}\}\lambda_{min}\{M(q)\}/2}}{\lambda_{max}\{M(q)\}},$$

$$\gamma_1 = \frac{\delta\alpha}{\tanh(\alpha\sigma)}, \ \gamma_2 = 2c_1 + \lambda_{max}\{F_d\},$$

$$\gamma_3 = k_{V_m 1}\sqrt{n} + \sigma\lambda_{max}\{M(q)\},$$

$$c_1 = k_{V_m 1}\|\dot{q}_d\|_M, \ d > 0,$$

$$\gamma_4 = \lambda_{max}\{k_v\} + \lambda_{max}\{k_p\} + \gamma_1,$$

$$\gamma_5 = \lambda_{max}\{M(q)\}\lambda_{max}\{A\} + \gamma_2,$$

$$\gamma_6 = k_{V_m 1}\sqrt{n} + \gamma_3$$

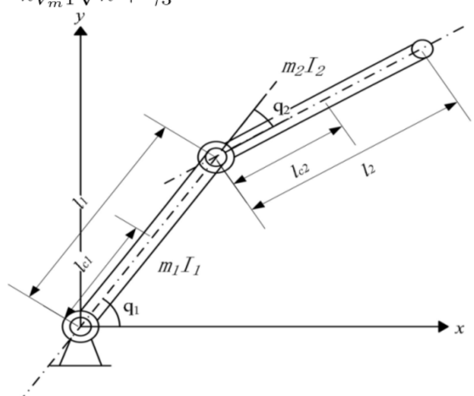

Figure 2: Robot manipulator of 2 link revolute arm

6. Case study

In the design of robots, the equations of motion are important to be considered. The Euler-Lagrange equations are used to describe the mechanical system subject to holonomic constraints. The Euler-Lagrange approach has a simple derivation of these equations from Newton's Second Law for a one-degree-of-freedom system. In order to determine the Euler- Lagrange equations in a specific situation, one has to form the Lagrangian of the system, which is the difference between the kinetic energy and the potential energy [21]. The Euler-Lagrange equations have several very important properties that can be exploited to design and analyze feedback control algorithms. Among these are explicit bounds on the inertia matrix, linearity in the inertia parameters, and the so-called skew symmetry and passivity properties.

The adaptive controlling scheme which proposed in this study is applied for two link robot manipulator as shown in Figure 2 to evaluate the controller performances and verifying the control algorithm. Hence, the dynamic equation can be derived as follows: The kinetic energy is a quadratic function of the vector $\dot{q}$ of the form:

$$K = \frac{1}{2}\sum_{i,j}^{n} d_{i,j}(q)\dot{q}_i\dot{q}_j = \frac{1}{2}\dot{q}^T M(q)\dot{q} \tag{20}$$

And the potential energy $P = P(q)$which is given by:

$$P_i = G^T r_{ci} m_i \tag{21}$$

Where G is vector giving the direction of gravity in the inertial frame and the vector r_{ci} gives the coordinates of the centre of mass of link i. So, the Euler-Lagrange equations for such a system can be derived as follows:

$$L = K - P$$
$$= \frac{1}{2}\sum_{i,j}^{n} d_{i,j}(q)\dot{q}_i\dot{q}_j - P(q) \tag{22}$$

The equations of motion related to manipulator are written as [21]:

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}} - \frac{\partial L}{\partial q} = \tau \tag{23}$$

or

$$\frac{d}{dt}\frac{\partial K}{\partial \dot{q}} - \frac{\partial K}{\partial q} + \frac{\partial P}{\partial q} = \tau \tag{24}$$

From (24) the dynamic model in equation (1) is generated. For implementing adaptive control (10), equation (1) can be re-arranged in the following form with neglecting viscous friction coefficient matrix to give

$$M(q)\ddot{q} + V_m(q,\dot{q})\dot{q} + G(q) = \tau \tag{25}$$
$$\tau = Y(q,\dot{q},\ddot{q})\theta$$

Where $Y(q,\dot{q},\ddot{q}) \in \mathbb{R}^{2\times r}$ is the dynamic regressor matrix for 2- link robot manipulator and θ is parameter vector containing the robot and payload parameters. Let the parameters be:

$$\theta_1 = m_2.l_{c2}^2 + I_2,\ \theta_2 = m_2.l_{c2}.l_1,$$
$$\theta_3 = m_1.l_{c1}^2 + m_2.l_1^2 + I_1,$$
$$\theta_4 = m_1.l_{c1} + m_2.l_1, \theta_5 = m_2.l_{c2}$$

Therefore, for two link robot the Equation (25) can be written as [21]:

$$\begin{bmatrix} m_{aa} & m_{au} \\ m_{ua} & m_{uu} \end{bmatrix} \begin{Bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{Bmatrix} + \begin{bmatrix} h\dot{q}_2 & h(\dot{q}_1+\dot{q}_2) \\ -h\dot{q}_1 & 0 \end{bmatrix} \begin{Bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{Bmatrix} + \begin{bmatrix} G_a \\ G_u \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \tag{26}$$

with

$$m_{aa} = m_1.lc_1 + m_2.(l_1^2 + lc_2^2 + 2.l_1.lc_2.\cos(q_2)) + I_1 + I_2$$
$$m_{au} = m_{ua} = m_2.(lc_2^2 + l_1.lc_2.\cos(q_2)) + I_2$$
$$m_{uu} = m_2.lc_2^2 + l_1.lc_2.\cos(q_2) + I_2$$
$$h = -m_2.l_1.lc_2.\sin(q_2)$$
$$G_a = (m_1.lc_1 + m_2.l_1)(g.\cos(q_1)) + m_2.lc_2.g.\cos(q_1+q_2)$$
$$G_u = m_2.lc_2.\cos(q_1+q_2)$$

and $lc_1 = lc_2 = 0.5$.

So, the above expressions change to

$$m_{aa} = \theta_1 + \theta_3 + 2.\theta_2\cos(q_2)$$
$$m_{au} = m_{ua} = \theta_1 + \theta_2\cos(q_2)$$
$$m_{uu} = \theta_1$$
$$h = -\theta_2.\sin(q_2)$$
$$G_a = \theta_4.g.\cos(q_2) + \theta_5.g.\cos(q_1+q_2)$$
$$G_u = \theta_5.\cos(q_1+q_2)$$

The Regressor matrix is a 2 x 5 matrix with following elements:

$$Y(q,\dot{q},\ddot{q}) = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \end{bmatrix}$$
$$a_{11} = a_{21} = \ddot{q}_1 + _2,\ a_{13} = \ddot{q}_1,\ a_{14} = g.\cos(q_1),$$
$$a_{15} = g.\cos(q_1+q_2),\ a_{25} = \cos(q_1+q_2),$$
$$a_{23} = a_{24} = 0,\ a_{22} = \ddot{q}_1\cos(q_2) + (\dot{q}_1^2).\sin(q_2)$$
$$a_{12} = (2.\ddot{q}_1 + \ddot{q}_2).\cos(q_2) - (\dot{q}_1^2 + 2.\dot{q}_1.\dot{q}_2).\sin(q_2)$$

According to Equation (15), the velocity estimator formula for two link robot becomes

$$\dot{\tilde{\vartheta}} = -A\tanh(\tilde{\vartheta}) + B\dot{e}$$
$$= -\begin{bmatrix} a_1 & 0 \\ 0 & a_2 \end{bmatrix}\tanh(\tilde{\vartheta}) + \begin{bmatrix} b_1 & 0 \\ 0 & b_2 \end{bmatrix}\dot{e} \tag{27}$$

and the parameter estimation formula becomes

$$\dot{\hat{\theta}} = \Gamma\left[-Y^T(q_d,\dot{q}_d,\ddot{q}_d)\dot{e} + \xi Y^T (q_d,\dot{q}_d,\ddot{q}_d)\left[\tanh(\vartheta) - \tanh(\sigma e)\right]\right] \tag{28}$$

Where Γ is a positive definite matrix represented as:

$$\Gamma = \begin{bmatrix} \Gamma_1 & 0 & 0 & 0 & 0 \\ 0 & \Gamma_2 & 0 & 0 & 0 \\ 0 & 0 & \Gamma_3 & 0 & 0 \\ 0 & 0 & 0 & \Gamma_4 & 0 \\ 0 & 0 & 0 & 0 & \Gamma_5 \end{bmatrix}$$

Therefore, the control law given in Equation (10) can be applied for the controller as in Equation (29). Table I listed the numerical values of the important parameters of the robot.

$$\tau = Y(q_d,\dot{q}_d,\ddot{q}_d)\hat{\theta} + \begin{bmatrix} k_v & 0 \\ 0 & k_v \end{bmatrix}\tanh(\tilde{\varphi}) + \begin{bmatrix} k_p & 0 \\ 0 & k_p \end{bmatrix}\tanh(\sigma e) \tag{29}$$

Table I. Robot parameters

Parameter	Description	Value	Unit
m_1	Mass of link 1	10	kg
m_2	Mass of link 2	5	kg
l_1	Length of link 1	1	m
l_2	Length of link 2	1	m
I_1	Inertia of link 1	10/12	$\mathrm{kg.m^2}$
I_2	Inertia of link 2	5/12	$\mathrm{kg.m^2}$

7. Simulation

The MATLAB/SIMULINK environment was used to perform the simulations in this study. Figure 3 illustrates the Simulink diagram of the control scheme strategy of two link robot manipulator system. The simulation consists of robot manipulator system, saturation filters, adaptive controller, velocity estimator, parameter estimator, trajectory that must followed and optimization block used for selecting the controlling parameters which based on optimal tracking error constrain. It also has three outputs which are the first joint displacement (position), q_1, the second joint displacement (position), q_2 and torque outputs. The parameters given in Table I, were used during the simulation. Also the desired trajectory for the both two links joints are given by the following equation

$q_{d1} = q_{d2} = -90° + 52.5(1 - \cos 1.26t)$

The initial positions and velocities for both joints are $(-90°, 30°)$ and $(0, 0)$ respectively. Equations (26-29) are formulated in MATLAB/SIMULINK environment as given in the appendix A. The tuned and limited parameters are selected to be as follows:

$K_v = \text{daig}\{10, 10\}, \; K_p = \text{daig}\{240, 240\},$

$A = \text{daig}\{10, 10\}, \; B = \text{daig}\{10, 10\},$

$\Gamma = \text{daig}\{1.2, 3.36, 7.44, 19.33, 2.42\}, \; \sigma = 6620$ and $\xi = 0.04$

While the maximum/minimum values of actuators torque inputs, that used for joint 1 and 2, are chosen to be as ± 150 and ± 35 respectively.

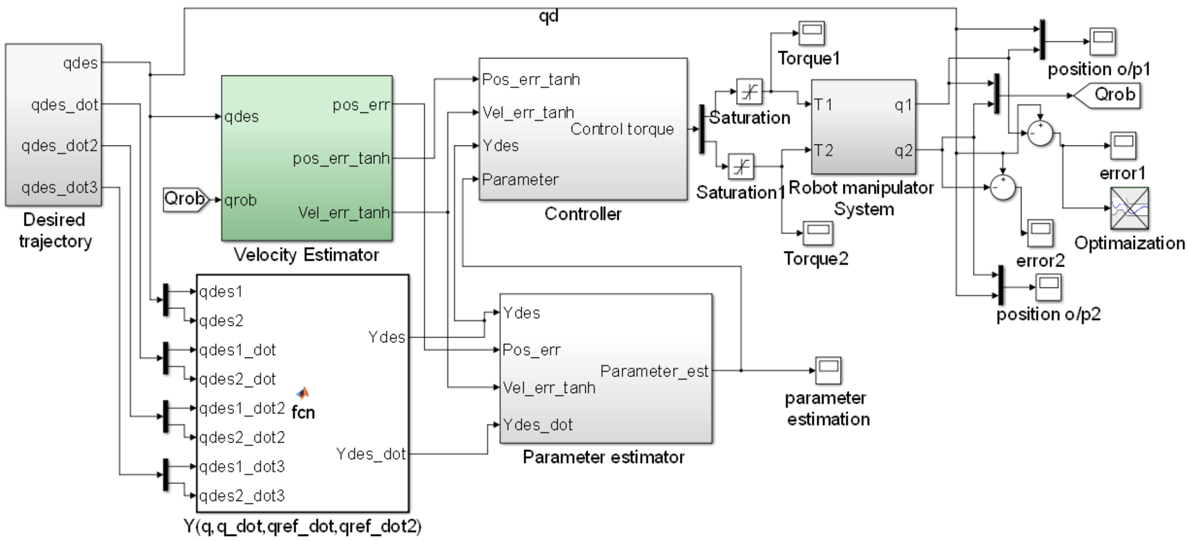

Figure 3: Matlabsimulink of proposed controlling algorithm.

Figure 4 illustrates the position performances for links joints 1 and 2. The figure shows that the desired trajectory and position of first joint are started from $-90°$ as initial position while the position of second joint started from $30°$. Also, it can be seen that the position performances of two joints are successfully tracking the desired trajectory. While the tracking errors for q_1 and q_2 against q_d are illustrated in Figure 5. It is clear that the tracking errors converge to very small value close to zero. The torques control inputs for the joints 1 and 2 are depicted in Figures 6 and 7 respectively. The figures reveal that both of input torques are not overcome the bounded limits which are 150 N.m for first joint and 35 for second joint. Figure 8 illustrates the parameter estimates.

The simulations reveals that the proposed adaptive controller work efficiently since the tracking errors vanish as the time increases, also the controller presents fast settling time of the tracking error $e(t)$. The explanation of this is that the proposed controller incorporates the extra gain σ whose numerical value has effect in the settling time. A lower value of σ leads to a slow settling time.

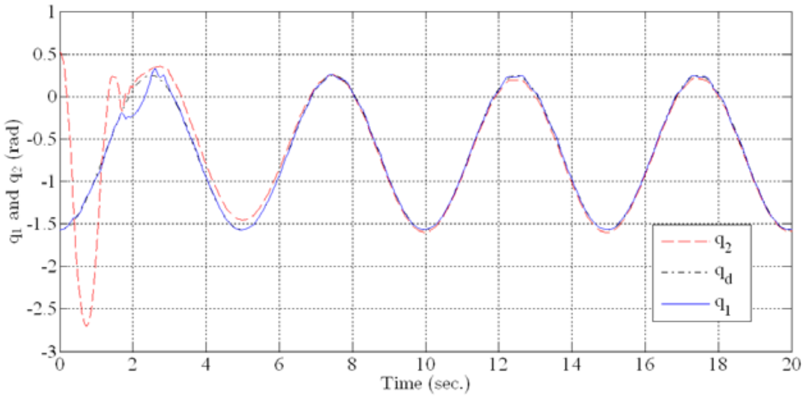

Figure 4: Position performances for joints 1 and 2 tracking desired trajectory.

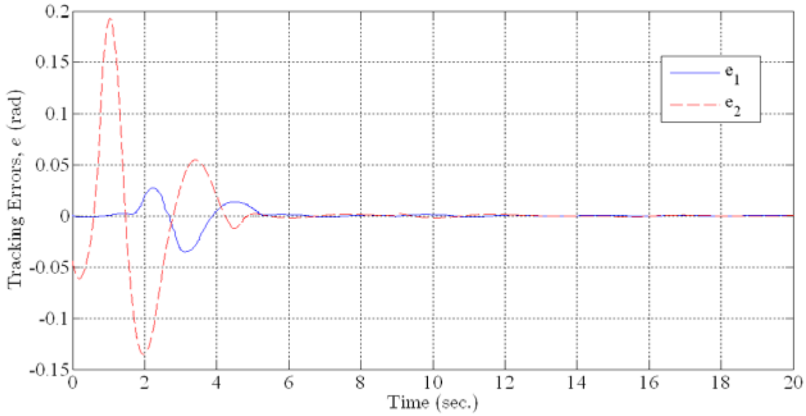

Figure 5: Position tracking errors for joints 1 and 2 against desired trajectory.

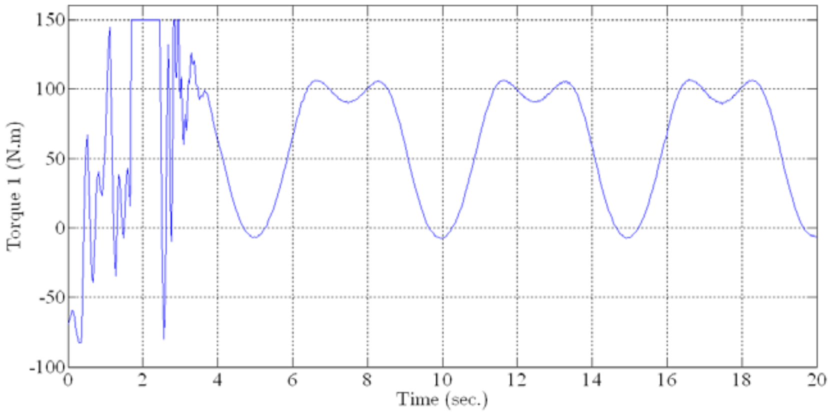

Figure 6: Actuator torque input for joints 1.

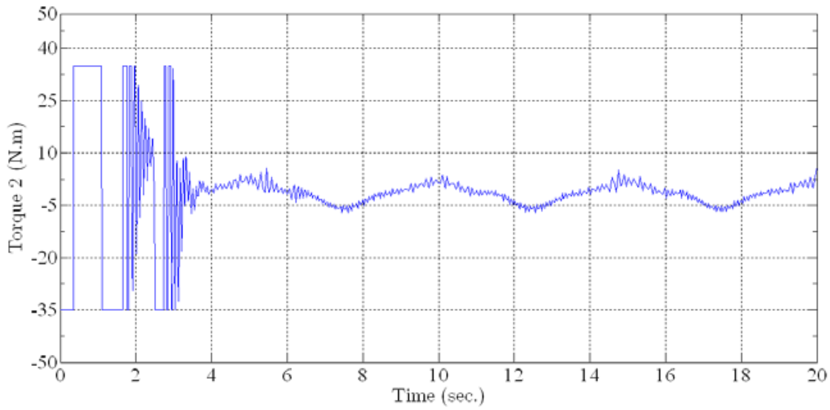

Figure 7: Actuator torque input for joints 2.

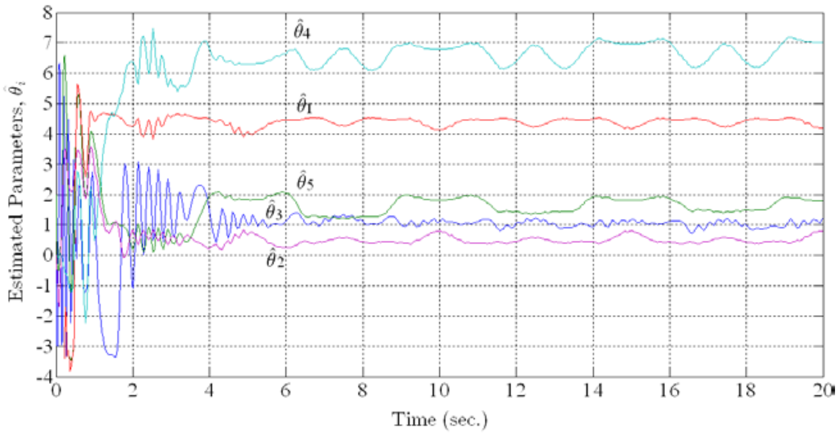

Figure 8: Adaptive controller parameter estimates.

8. Comparative study

For the purpose of demonstrating the efficiency of controller proposed in this work over related proposed controllers, the simulation results from the proposed adaptive controller compared with simulation results of a global output feedback controller which presented by Zergeroglu [2] and Zhang [3] which are using much related approach with different control law algorithm. Figure 9 illustrates the tracking errors and torques outputs for the global output feedback controller proposed by Zhang [3]. Figure 10 depicted the parameters estimated for this controller. In spite of very small differences between model parameters of robot used in this work with that one used by Zhang [3], the behaviour of results are the same. As well as the comparisons between results of current work, as presented in Figures 5, 6 and 7, and results of reference [3], as presented in Figures 9 and 10, show that both of controller work efficiently because when the time increase the tracking errors are vanished, although the settling time of proposed controller is less than that settling time of the controller proposed by Zhang [3].This is because of the low values of σ as mentioned in the previous section.

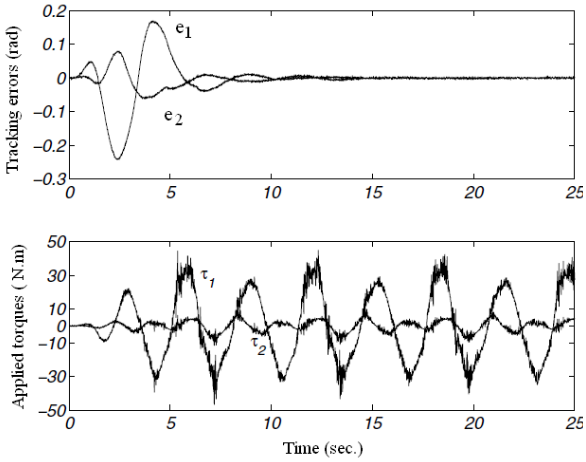

Figure 9: The tacking error and applied torques obtained by using controller presented by references [2] and [3].

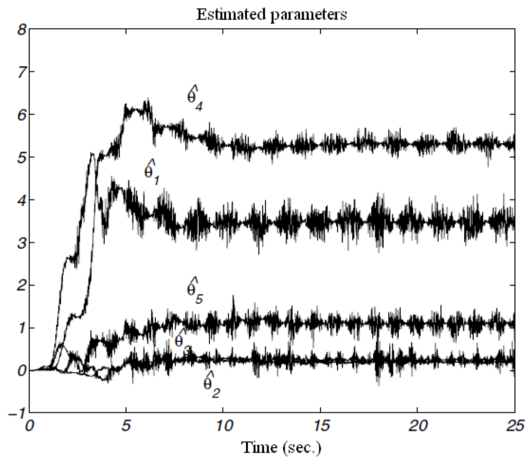

Figure 10: Estimated parameters of the controller presented by references [2] and [3].

9. Conclusion

In this paper, the solution to the problem of output feedback with all kinematics parameters unknown of robot manipulator is studied. The solution presented an adaptive control algorithm based on position measurement only. For each manipulator joint, constrains on torque of actuators are considered as a bounded control input. The adaptive controller is tested upon two link manipulator. The investigation of the tracking control is implemented under the following conditions; joint position feedback, parameter estimation and constrained torque. The design of model is successfully implemented in Matlab/Simulink and the results are provided. The tracking error for the joint position measurements is within 0.001 radians or 0.03 degrees. The settling time is less than 6 seconds for the steady state. The proposed controller results are validated to controller using similar approach with different control law algorithm. The future work suggested adopting this type of controller based on EMG as input signals.

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Appendix A

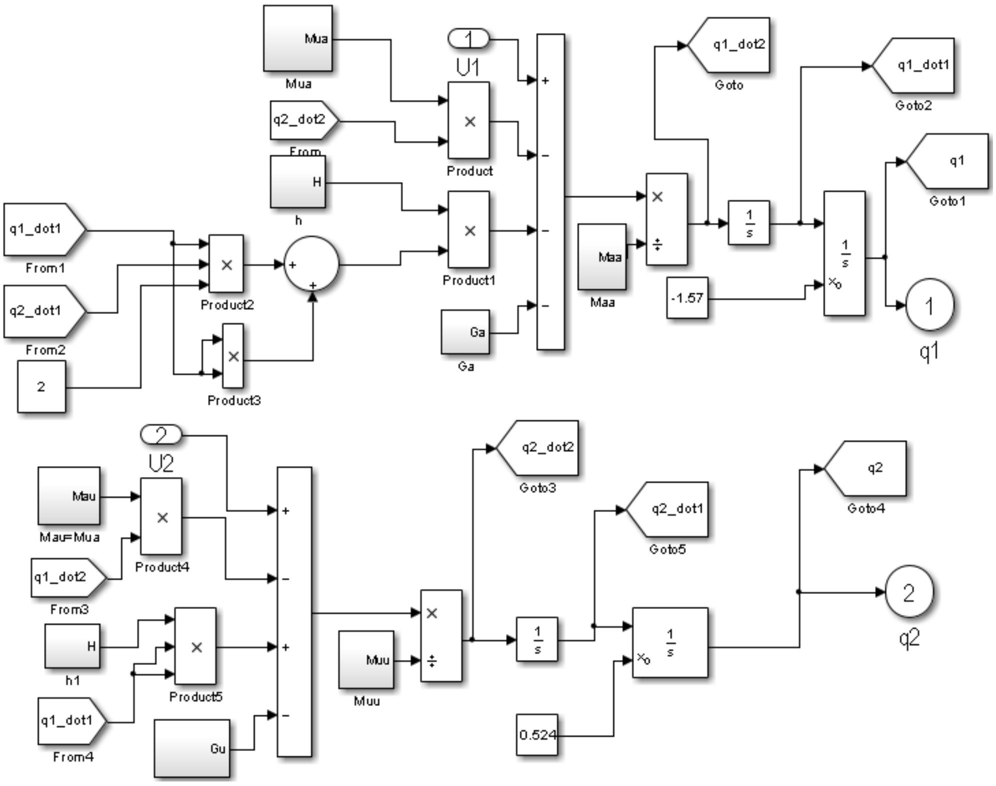

Figure A1: 2-link robot manipulator modelled in Matlab/Simulink Block diagram.

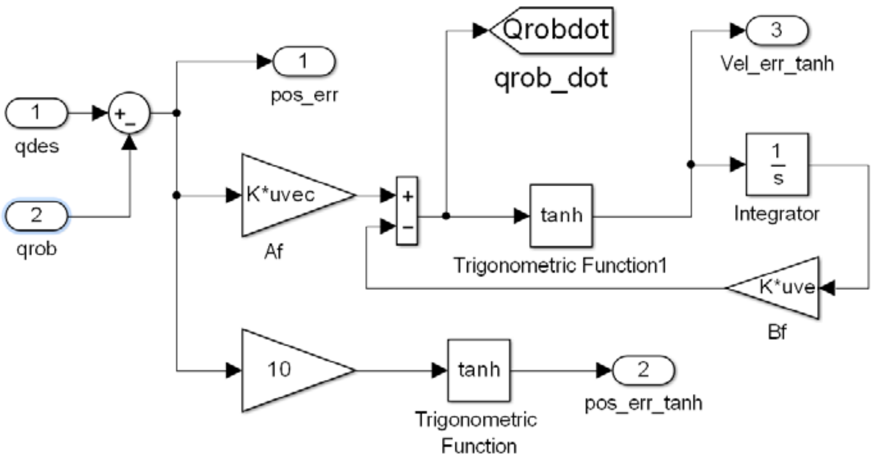

Figure A2: Velocity estimator represented in Matlab/Simulink Block diagram.

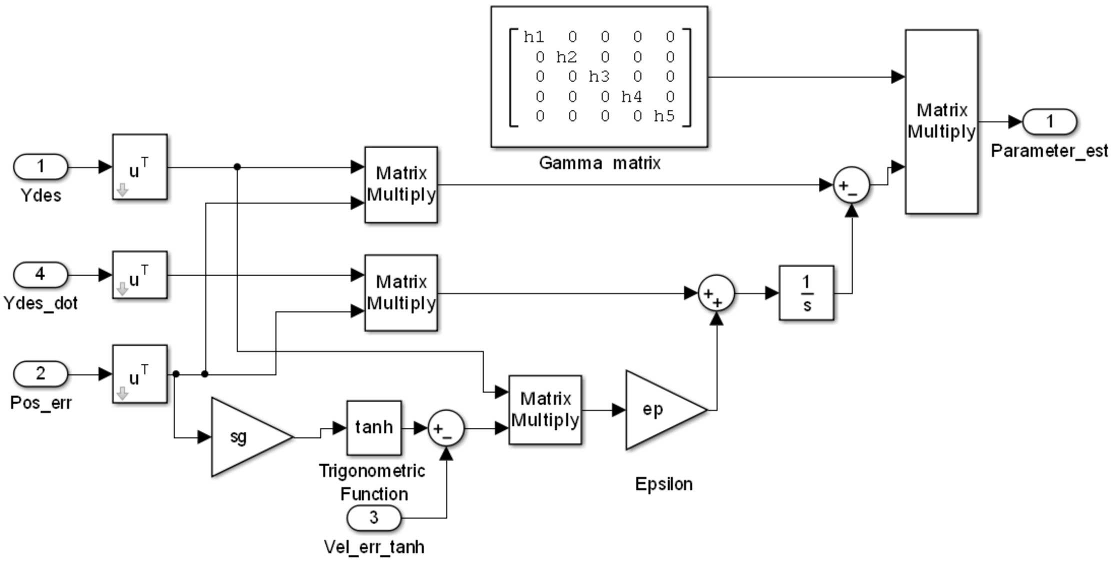

Figure A3: Parameters estimation represented in Matlab/Simulink Block diagram.

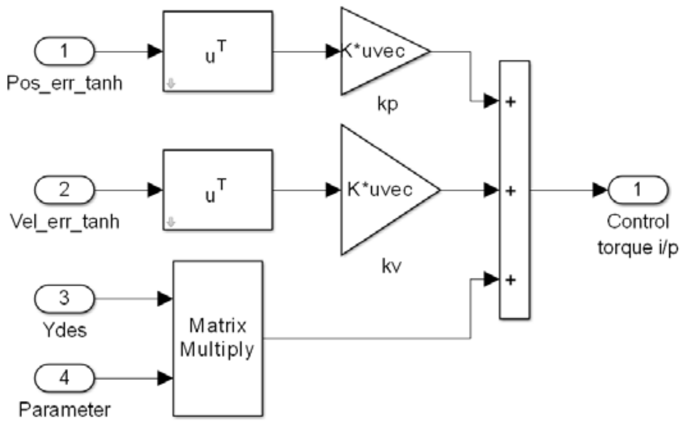

Figure A4: Control law represented in Matlab/Simulink Block diagram.

السيطرة المكيفة لمناور روبوت باستخدام سرعة مخمنة وعزم مقيد

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جامعة النهرين

الخلاصة

يقصد بمشكلة التغذية العكسية لمخرج الروبوت المناور على انها المنظومة المسيطر عليها عند توفر قراءات لموقع المفصل. في هذه الدراسة, المعاملات الحركية للربوت المناور اعتبرت غير معلومة والمناورعليه ان يتبع المسار المفترض. لذلك جرى التحقق من تصميم مسيطر متكيف لربوت مناور بالاعتماد على السرعة المخمنة. وفقا لكون المشغلات الميكانيكية العملية في الربوت المناور تكون محددة القدرة لذلك اخذ بنظر الاعتبار في هذه الدراسة تقييد العزم الداخل للمناور. خوازمية السيطرة المقترحة تم تطبيقها على مناور ثنائي الذراع لتقييم فعالية المسيطر. تم اختيار وتصميم المعاملات والتي تضمن اداء السيطرة للمنظومة المغلقة الدورة عن طريق استخدام طريقة تحديد المخرجات المثلى. تم الحصول على الاداء ونتائج المسيطر المقترح عن طريق المحاكاة العددية.