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Trajectory Tracking Control of Two-link Robotic Manipulator Using PID and MPC Controllers

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Abstract

This paper discusses the difference between two tracking control strategies for a two-link robotic manipulator and compares the tracking results of the two strategies, in terms of accuracy and overshoots prevention. The design and simulation of the control approaches are based on the development of a nonlinear model for the complex dynamics of the manipulator system. The system modeling is based on Euler-Lagrange equations. The first strategy is a Proportional Integral Derivative (PID) control. Its design is based on the trial and error online tuning method, which is applied directly to control the two-joints of the robotic manipulator. On the other hand, the second strategy is a novel Model Predictive Control (MPC) strategy, which its design is based on feedback linearization analysis technique that utilizes the nonlinear model of the manipulator's complex dynamics to design a feedback linearization control strategy to work as a primary control loop. Then based on the resulted linear model of feedback linearized system, a linear MPC controller is designed and implemented as a secondary control loop. The results of the experimental simulations showed, particularly by comparing the time responses, that the MPC control strategy has a performance superior to the PID control strategy. Overshoots appeared when using the PID control strategy but they disappeared when the MPC control strategy was applied.

I. Introduction

The research studies and development of control strategies for robotic manipulators are increasing day by day in industrial applications, where robotic manipulators play an important role in the industry to increase quality and productivity, because they have highly greater flexibility and with improved accuracy, they can outperform the normal fixed automation machines. The robotic manipulators, particularly during industrial operations, must be able to follow steadily certain trajectories depending on the type of the end effector's job. Robotics are mechatronic systems and require expertise in multi engineering domains. The control of a robotic manipulator is the most challenging task, because even a one link manipulator has a nonlinear complex dynamic behavior [1]. Due to the nonlinear nature of the two-link manipulator, special control systems are implemented to move the robotic links accurately to the desired positions [2]. The main purpose of this research is to make a performance comparison of the two-links robotic manipulator using a two different control strategy to accurately move the robotic manipulator in the desired trajectory. Overshoots demand special attention in industrial tasks that require high speed and accurate operations of robots in the presence of obstacles [3].

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Therefore, in this study, a novel control strategy based on Model Predictive Control (MPC) will be used to stabilize each link of the manipulator in a specified collision-free trajectory and then comparing it with the performance of the Proportional Integral Derivative (PID) control strategy based on trial & error design, which is the most commonly practiced in industrial control, due to their easy implementation in both simulation and hardware systems [4,2]. Both of the control strategies (PID & MPC) are applied and considered to show, if they can drive the manipulator system to specific angles and to investigate, the effectiveness of the novel MPC strategy to eleminate overshoots compared to the common industrial PID control strategy designed based on trial & error method.
There are a lot of research work regarding the improvement of the robotic system performance, e.g., in [5], the research introduced a dual design of PID controller architecture process that aims to improve system performance by reducing overshoot and conserving electrical energy, it was found to be an effective solution for reducing overshoot and saving electrical energy in systems. In [6] used model predictive controller for trajectory tracking of a data-based model of a two-link robotic manipulator. The results have shown that low-order and data-compliant models can follow trajectories with high precision. In [7], the research introduced, how to derive an ideal transformed input based on dynamic model, also in this work, the same idea is implemented, which is the use feedback linearization analysis and control technique. In [8], the research proposed the use of a nonlinear MPC for controlling robotic manipulators; the results have confirmed the robustness and effectiveness of the nonlinear MPC. In [9], the work included a control strategy for two degrees of freedom robotic arm using dynamic model feedback linearization and model predictive controller, the simulation results showed that no overshoot has been canceled. In [10], a model predictive control for trajectory tracking control of a two degrees of freedom selective compliant assembly robot arm under an external force acting to the tip of the robot along the trajectory was performed. According to simulation studies, successful results were obtained. In [11], the research introduced MPC controller design for linearized two-link robot arm model to control the movements of the robot arm. The results revealed that the linearized MPC controls the robot arm successfully in a very short time.

The structure of this paper is as following, in section II, a description of the two-link robotic manipulator is provided with its dynamic model by using the Euler-Lagrange approach, along with deriving the block diagram of the nonlinear model. Section III presents first the proportional integral derivate control strategy, which uses trial and error method. Second, the feedback linearization of the nonlinear dynamics is presented, which based on the linearization analysis technique, linearization by using feedback, and on feedback linearization control as feed forward control. Third, a model predictive controller and its design is introduced by using feedback linearized model of the nonlinear dynamics of the robotic manipulator. Simulation models of both PID & MPC control strategies and the simulation results are presented in section IV. In section V, the conclusion is presented. Finally, the references are given in section VI.

II. Modelling of The Two –Link Robotic Manipulator [12]

A robotic manipulator is a type of mechanical arm, which is programmable to functions similar to a human arm. The links of such a manipulator are connected by joints that enable rotational movement like an articulated robot. The links of the manipulator can be viewed as a kinematic chain [13]. Fig. 1, below shows the schematic diagram of two links robotic manipulator.

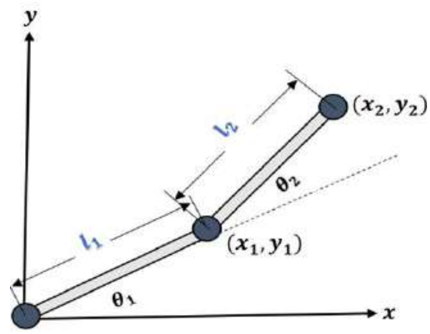

Figure 1. Two-links robotic manipulator

The manipulator system consists of two bars with masses m_1 and m_2. The bars have lengths l_1 and l_2. Let $\theta_1$and θ_2 denote the joint angles in which the first bar rotates around the origin and the second bar rotates around the endpoint of the first bar, respectively. Moreover, τ_1 and τ_2 denote the torques of the coordinates exerted on the joints θ_1 and θ_2. Also, I_1 and I_2 are assigned to the inertias of motors which drive the bars. Besides, ω_1 and ω_2 denote the angular velocities, while, s_1 and s_2 denote the linear velocities and the gravitational constant is assigned by g. The effect of friction forces is assumed here to be negligible.

A. Dynamics of the Two-Link Robotic Manipulator

The dynamic model of the manipulator is obtained by solving the Euler-Lagrange equations and these equations are based on the partial derivatives of the Lagrangian.

The first step in deriving the equations of motion using the Lagrangian approach is to find the kinetic energy KE and the potential energy PE of the manipulator system.

The equations for the x-position and the y-position of link1 are given by:

$$x_1 = l_1 \cos\theta_1 \rightarrow \dot{x}_{1=-} l_1 \sin\theta_1 . \dot{\theta}_1 \tag{1}$$

$$y_1 = l_1 \sin\theta_1 \rightarrow \dot{y}_{1=} l_1 \cos\theta_1 . \dot{\theta}_1 \tag{2}$$

$$s_1^2 = \dot{x}_1{}^2 + \dot{y}_1{}^2 \tag{3}$$

$$KE_1 = \frac{1}{2} m_1 s_1{}^2 + \frac{1}{2} I_1 \omega_1{}^2 \tag{4}$$

Where $\omega_1 = \dot{\theta}_1$,

$$KE_1 = \frac{1}{2} m_1 l^2{}_1 \dot{\theta}_1{}^2 + \frac{1}{2} I_1 \dot{\theta}_1{}^2 \tag{5}$$

$$KE_1 = \frac{1}{2}(m_1 l^2{}_1 + I_1)\dot{\theta}_1{}^2 \tag{6}$$

$$PE_1 = m_1 g l_1 \sin\theta_1 \tag{7}$$

The equations for the x-position and the y-position of link2 are given by:

$$x_2 = x_1 + l_2 \cos(\theta_1 + \theta_2) \tag{8}$$

$$y_2 = y_1 + l_2 \sin(\theta_1 + \theta_2) \tag{9}$$

$$s_2^2 = \dot{x}^2{}_2 + \dot{y}^2{}_2 \tag{10}$$

Where $\omega_2 = \dot{\theta}_1 + \dot{\theta}_2$,

$$KE_2 = \frac{1}{2} m_2 s_2^2 + \frac{1}{2} I_1 (\dot{\theta}_1 + \dot{\theta}_2) \tag{11}$$

$$KE_2 = \frac{1}{2} m_2 l^2{}_1 \dot{\theta}_1^2 + \frac{1}{2} m_2 l^2{}_2 (\dot{\theta}_1 + \dot{\theta}_2)^2 + m_2 l_1 l_2 \dot{\theta}_1 (\dot{\theta}_1 + \dot{\theta}_2) \cos\theta_2 + \tfrac{1}{2} I_2 (\dot{\theta}_1 + \dot{\theta}_2)^2 . \tag{12}$$

$$PE_2 = m_2 g l_1 \sin\theta_1 + m_2 g\, l_2 \sin(\theta_1 + \theta_2) \tag{13}$$

The total kinetic energy of the manipulator system is:

$KE = KE_{1+} KE_2$

$$KE = (\frac{1}{2} m_1 l^2{}_1 + \frac{1}{2} m_2 l^2{}_1 + \frac{1}{2} m_2 l_2{}^2 + m_2 l_1 l_2 \cos\theta_2 + \frac{1}{2} I_1 + \frac{1}{2} I_2)\dot{\theta}^2{}_1 + (\frac{1}{2} m_2 l^2{}_2 + \frac{1}{2} I_2)\dot{\theta}_2 + (m_2 l^2{}_2 + m_2 l_1 l_2 \cos\theta_2 + I_2)\dot{\theta}_1 \dot{\theta}_2 . \tag{14}$$

The potential energy of the manipulator system is:

$PE = PE_{1+} PE_2$

$$PE = (m_1 + m_2) g l_1 \sin\theta_1 + m_2 g\, l_2 \sin(\theta_1 + \theta_2). \tag{15}$$

To deriving the dynamics of the two-link robotic manipulator, first applying the Lagrange equation as following:

$L = KE - PE$

$$L = (\frac{1}{2} m_1 l^2{}_1 + \frac{1}{2} m_2 l^2{}_1 + \frac{1}{2} m_2 l_2{}^2 + m_2 l_1 l_2 \cos\theta_2 + \tfrac{1}{2} I_1{}^2 + \tfrac{1}{2} I_2{}^2)\dot{\theta}^2{}_1 + \left(\tfrac{1}{2} m_2 l^2{}_2 + \tfrac{1}{2} I_2\right)\dot{\theta}_2{}^2 + (m_2 l^2{}_2 + m_2 l_1 l_2 \cos\theta_2 + I_2)\dot{\theta}_1 \dot{\theta}_2 - [(m_1 + m_2) g l_1 \sin\theta_1 + m_2 g\, l_2 \sin(\theta_1 + \theta_2)]. \tag{16}$$

Second applying the following Euler-Lagrange equation:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \frac{\partial L}{\partial \theta_i} = \tau_i \tag{17}$$

τ_i denotes the generalized coordinate torque exerted on joint θ_i.

For the coordinate θ_1 Euler-Lagrange equation is:

$$\tau_1 = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_1}\right) - \frac{\partial L}{\partial \theta_1} \tag{18}$$

$$\frac{d}{dt}\left(\frac{d}{d\dot{\theta}_1}\right) = [m_1 l_1{}^2 + m_2 l_1{}^2 + m_2 l_2{}^2$$
$$+2_2 l_1 l_2 \cos\theta_2 + I_1 + I_2]\,\ddot{\theta}_1$$
$$+[m_2 l_2{}^2 - m_2 l_1 l_2 \cos\theta_2\, I_2]\ddot{\theta}_2$$
$$+[2m_2 l_1 l_2 \sin\theta_2]\dot{\theta}_1\dot{\theta}_2$$
$$+\,[m_2 L_1 L_2 \cos\theta_2]\dot{\theta}_2{}^2. \quad (19)$$

$$\frac{dL}{d\theta_1} = -(m_1 + m_2) g l_1 \cos\theta_1$$
$$-m_2 g\, l_2 \cos(\theta_1 + \theta_2). \quad (20)$$

$$\tau_1 = [\,[m_1 + m_2] l_1{}^2 + m_2 l_2{}^2 +$$
$$2m_2 l_1 l_2 \cos\theta_2 + I_1 + I_2]\ddot{\theta}_1 +$$
$$[m_2 l_2{}^2 + m_2 l_1 l_2 \cos\theta_2 + I_2]\ddot{\theta}_2 -$$
$$[2m_2 l_1 l_2 \sin\theta_2]\dot{\theta}_1\dot{\theta}_2 -$$
$$[m_2 l_1 l_2 \sin\theta_2]\dot{\theta}_2{}^2 + (m_1 +$$
$$m_2) g l_1 \cos\theta_1 + m_2 g l_2 \cos(\theta_1 + \theta_2). \quad (21)$$

Similarly, for the coordinate θ2, the Euler-Lagrange's equation is:

$$\tau_2 = \frac{d}{dt}\left(\frac{d}{d\dot{\theta}_2}\right) - \frac{dL}{d\theta_2} \quad (22)$$

$$\frac{d}{dt}\left(\frac{d}{d\dot{\theta}_2}\right) =$$
$$[m_2 l_2{}^2 + m_2 l_1 l_2 \cos\theta_2 + I_2]\ddot{\theta}_1 +$$
$$[m_2 l_2{}^2 + I_2]\ddot{\theta}_2 +$$
$$[m_2 L_1 L_2 \sin\theta_2]\dot{\theta}_1\dot{\theta}_2. \quad (23)$$

$$\frac{dL}{d\theta_2} = -\,(m_2 l_1 l_2 \sin\theta_2)\dot{\theta}_1{}^2$$
$$-[m_2 l_1 l_2 \sin\theta_2]\dot{\theta}_1\dot{\theta}_2$$
$$-m_2 g l_2 \cos(\theta_1 + \theta_2). \quad (24)$$

$$\tau_2 = [m_2 l_2{}^2 + m_2 l_1 l_2 \cos\theta_2 + I_2]\ddot{\theta}_1$$
$$+[m_2 l_2{}^2 + I_2]\ddot{\theta}_2 + [m_2 l_1 l_2 \sin\theta_2]\dot{\theta}_1{}^2$$
$$+m_2 g l_2 \sin(\theta_1 + \theta_2). \quad (25)$$

B. Deriving Block Diagram of the Nonlinear Model

Starting by defining the following vectors and matrices:

$\theta_i = \begin{bmatrix}\theta_1\\ \theta_2\end{bmatrix}$, $\tau_i = \begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix}$, M= $\begin{bmatrix}M_{11} & M_{12}\\ M_{21} & M_{22}\end{bmatrix}$,

N= $\begin{bmatrix}N_{11} & N_{12}\\ N_{21} & N_{22}\end{bmatrix}$, C= $\begin{bmatrix}C_{11} & C_{12}\\ C_{21} & C_{22}\end{bmatrix}$ and G = $\begin{bmatrix}G_{11}\\ G_{12}\end{bmatrix}$.

$M_{11} = [(m_1 + m_2) l_1{}^2 + m_2 l_2{}^2 + 2m_2 l_1 l_2 \cos\theta_2 + I_1 + I_2]$.

M_{12}=$[m_2 l_2{}^2 + m_2 l_1 l_2 \cos\theta_2 + I_2]$.

M_{21}=$[m_2 l_2{}^2 + m_2 l_1 l_2 \cos\theta_2 + I_2]$.

M_{22}=$[m_2 l_2{}^2 + I_2]$.

N_{11} = 0

N_{12} = $[-m_2 l_1 l_2 \sin\theta_2]$.

N_{21} = $[m_2 l_1 l_2 \sin\theta_2]$.

N_{22} = 0.

C_{11} = $[-m_2 l_1 l_2 \sin\theta_2]$.

C_{12} = $[-m_2 l_1 l_2 \sin\theta_2]$

C_{21}= 0

C_{22}= 0

G_{11}=$[(m_1 + m_2) g l_1 \cos\theta_1 + m_2 g l_2 \cos(\theta_1 + \theta_2)]$

G_{12}=$[m_2 g l_2 \cos(\theta_1 + \theta_2)]$

Where:

M: is the inertia matrix,

G: is a vector of gravity torque,

N and **C:** are the matrices of, Coriolis and Centrifugalforces.

To simplify modeling, (21) and (25) are placed in matrix form as following:

$$\tau_i = M\ddot{\theta}_i + N\dot{\theta}_i^{\,2} + C(\dot{\theta}_1\dot{\theta}_2) + G \tag{26}$$

$$\ddot{\theta}_i = M^{-1}\left[\tau_i - N\dot{\theta}_i^{\,2} - C(\dot{\theta}_1\dot{\theta}_2) - G\right] \tag{27}$$

The next Fig. 2, shows the block diagram of the two-link robotic manipulator mathematical model which is built from (27).

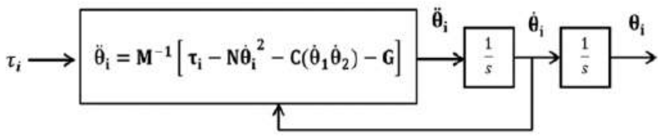

Figure 2. Block diagram of the two-link robotic manipulator mathematical model

III. The Control Strategies

In this section, the design and implementation of the control strategies are presented for trajectory tracking of a two-link robotic manipulator. Where, in the following, the PID controller is presented at first subsection. Then at the second subsection, the development of feedback linearization is presented to get an ideal linearization of the nonlinear dynamics. Moreover, at the third subsection, the model predictive controller and its design for the two-link robotic manipulator is developed by utilizing the feedback linearized system of the nonlinear dynamics. The main goal of this work is to determine the best stable control strategy that can accurately move the robotic manipulator along the desired trajectory.

A. Proportional Integral Derivative Control

The Proportional Integral Derivate Controller (PID) is implemented to control the two-link robotic manipulator. Two PID controllers are needed for each link. Since link1 and link2 are mechanically connected, therefore, they are dependent on each other. As a matter of fact, there is a strong interaction between the two links. So, the coupling effect needs to be decoupled so as to gain enough freedom in order to control each link freely [14]. The objective of the robotic manipulator control is to design the input torque as shown in (26), such that it drives the tracking error to zero. The tracking error is defined by the difference between the desired and the respective measured joint link angle as following:

$$e_i(t) = \theta_{id}(t) - \theta_{im}(t) \tag{28}$$

In a typical PID method, the controller corrects the error between the desired input value θ_{id} and the measured value θ_{im}. Since the actual position is the measured signal θ_{im}, and the PID control law is expressed as:

$$u_{PID}(t) = K_p e(t) + K_I \int e(t)\,dt + K_D \frac{de(t)}{dt} \tag{29}$$

In this work, the controller parameters (K_P, K_I, K_D) are designed based on trial & error method. So, the proportional action is the main control, while the integral and derivative actions refine it. The controller gain, K_P, is adjusted with the integral K_I, and derivative K_D actions held at a minimum, until a desired output response is obtained [15,16]. In the next, Fig. 3, shows the general block diagram of a two-link robotic manipulator control loop using two PID controllers.

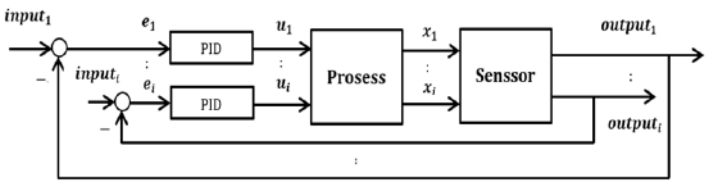

Figure 3. General structure of a robotic process control loop using two PID controllers

B. Feedback Linearization of the Non-linear Dynamics

The idea of feedback linearization is to perform a transformation on the system input that makes the system linear between new input and output. This transforms the nonlinear system dynamics into fully or partly linear ones [17].

1. Linearization analysis of the nonlinear model (by using feedback)

In this subsection, in order to clarify the possibility and the ability of application of the feedback linearization control technique, the nonlinear model of two-link robotic manipulator is analyzed and transformed to make the design possible and realizable. First of all, to achieve the transformation, some variables are needed to be reintroduced as following:

$$\theta_1 = x_1, \quad \dot{\theta}_1 = \dot{x}_1 = x_2, \quad \ddot{\theta}_1 = \dot{x}_2,$$

$$\theta_2 = x_3, \quad \dot{\theta}_2 = \dot{x}_3 = x_4, \quad \ddot{\theta}_2 = \dot{x}_4.$$

$\ddot{\theta}_1$ and $\ddot{\theta}_2$ are obtained from (21) and (25) respectively as following:

$$\ddot{\theta}_1 = \frac{1}{\left[[m_1 + m_2]l_1^{\,2} + m_2 l_2^{\,2} + 2m_2 l_1 l_2 \cos\theta_2 + I_1 + I_2\right]} * [\tau_1$$

$$-[m_2 l_2^{\,2} + m_2 l_1 l_2 \cos\theta_2 + I_2]\ddot{\theta}_2 + [2m_2 l_1 l_2 \sin\theta_2]\dot{\theta}_1\dot{\theta}_2$$

$$+[m_2 l_1 l_2 \sin\theta_2]\dot{\theta}_2^{\,2} - (m_1 + m_2) g l_1 \sin\theta_1 - m_2 g l_2 \sin(\theta_1 + \theta_2)] \tag{30}$$

and

$$\ddot{\theta}_2 = \frac{1}{[m_2 l_2^{\,2} + I_2]} * [\tau_2 - [m_2 l_2^{\,2} + m_2 l_1 l_2 \cos\theta_2 + I_2]\ddot{\theta}_1$$

$$-[m_2 l_1 l_2 \sin\theta_2]\dot{\theta}_1^{\,2} - m_2 g l_2 \sin(\theta_1 + \theta_2)] \tag{31}$$

The manipulator's state-space nonlinear model is as follows:

$$\dot{x}_1 = x_2, \qquad \dot{x}_2 = \ddot{\theta}_1,$$

$$\dot{x}_3 = x_4, \qquad \dot{x}_4 = \ddot{\theta}_2,$$

$$y_1 = \theta_1 = x_1, \qquad y_2 = \theta_2 = x_3.$$

To achieve feedback linearization here, the non-linearity must be separated and returned to the input, creating a system with separate linear dynamics and separate nonlinear static input function as demonstrated below:

$$\mathrm{U} = \begin{bmatrix} 0 \\ \ddot{\theta}_1 \\ 0 \\ \ddot{\theta}_2 \end{bmatrix} \tag{32}$$

The system state space equations are

$$\dot{X} = A.X + B.U$$

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} . \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} 0 \\ \ddot{\theta}_1 \\ 0 \\ \ddot{\theta}_2 \end{bmatrix} \tag{33}$$

$$Y = C.X$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} . \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} . \tag{34}$$

The transformed state space model, described by (33) and (34), has separated linear dynamics and nonlinear characteristics at the input interconnected through feeding back of the linear part states. This form clarifies the way of how to linearize the system by compensation of the nonlinear characteristics through feedback control as shown in the next subsection. Fig. 4, shows the separated nonlinear and linear parts of the two-link robotic manipulator with feedback interconnections.

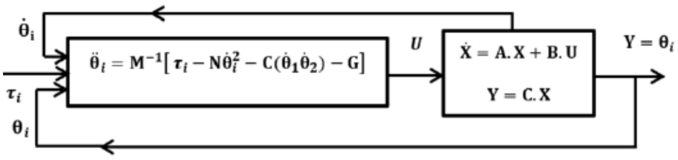

Figure 4. The transformed model of separate nonlinear characteristics and linear dynamics with feedback interconnections

2. *Design of the Feedback Linearization Control / Feed Forward Control*

The Feedback Linearization Controller (FLC) is an influential nonlinear controller for certain systems. This method is based on calculating the required manipulator torque using the nonlinear feedback control law. When all dynamic and physical parameters are known, a feedback linearization control works outstanding [18]. Similarly, feedforward control is used to compensate for measured disturbances before they affect the system output. Ideally, given a perfect model of the system and an error free measurement of the disturbances, it is possible to entirely eliminate the effect of the disturbances [19,20].In this paper, the feed forward control works as feedback linearization control. So, the state space system given in (33) and (34), is combined with a feed forward decision controller to reject the nonlinear input-disturbances shown in (32), and as consequence, results the ideal linearization for the model of the two-link robotic manipulator system. From (26) and (27), we get the feedback linearization control law as following:

$$\tau_i = M v_i + N \dot{\theta}_i^{\,2} + C(\dot{\theta}_1 \dot{\theta}_2) + G \tag{35}$$

Where v_i is the control signals vector and

$$v_i = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} \tag{36}$$

The following Fig. 5, presents the feedback linearization controller of the two-link robotic manipulator.

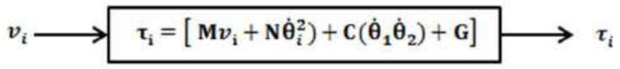

Figure 5. Feedback linearization controller for the two-link robotic manipulator

By using the feedback linearization controller to reject the nonlinear input disturbances of the robotic manipulator system, the ideal linearization for the non-linear dynamics of the robotic manipulator has been done. The following Fig. 6, presents the feedback linearization control loop, which product the ideal linearization of the two- link robotic manipulator model.

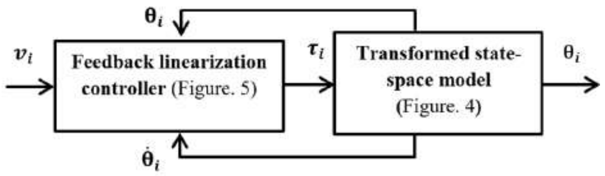

Figure 6. feedback linearization control loop of the two-link robotic manipulator

3. *MPC control design by utilizing the linearized model*

Model predictive control (MPC) is an advanced optimal control method, that has significant and widespread impact in control of industrial processes [21]. In order to implement this control strategy, the basic structure of MPC controller shown in Fig. 7, below has to be introduced. In MPC controller, a model is used to predict the future system outputs, based on the past and current values and on the optimal future control actions. These control actions are computed by an optimizer to minimize a cost function for a constrained dynamic system [22]. The MPC determines the control law implicitly. This shifts the effort for the design of a controller towards modeling of the process to be controlled [23].

The following Fig. 7, shows a typical structure of a general model predictive control system.

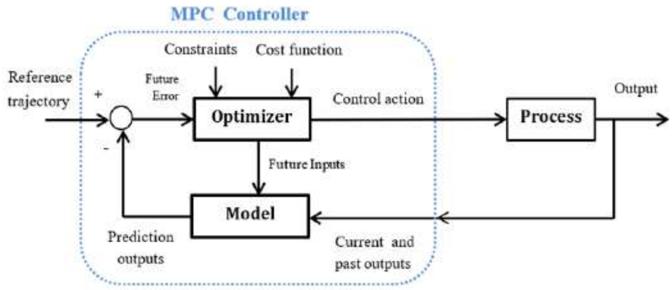

Figure 7. Typical structure of model predictive control

The controller is designed, so that the following cost function J is minimized:

$$J = \int_0^t e^2(n)dn \rightarrow min\,.$$

In this paper, three-steps MPC design for trajectory tracking control of a two-link robotic manipulator is implemented, where first, a feedback linearization algorithm is implemented as shown in Fig. 4 and second, a feedback linearization controller is developed as primary controller, see Fig. 5, so that to make the model of the manipulator system ideal linear as shown in Fig. 6. Once the ideal linear model was obtained, then as a next step, a linear model predictive control is designed based on the resulted linear model to function as secondary controller. Linear MPC control technique in closed loop can now be applied to make every link of the robotic manipulator follows its desired trajectory. Fig. 8 below shows the general structure of the two-link robotic manipulator linearized model, based on the feedback linearized model and the feedback linearization controller works as primary controller, and cascaded with a linear MPC secondary controller in closed loop.

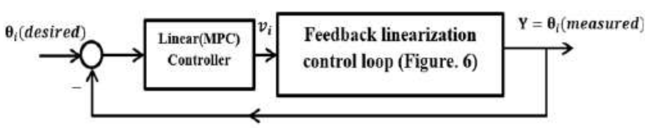

Figure 8. General structure of the linearized model of the robotic manipulator controlled with a linear MPC controller in closed loop

IV. Simulation and Results Discussion

In this section, the physical-mechanical parameters used in the simulation for both control strategies applied on the two-link robot manipulator system are presented in TABLE I. below. Then, in Sections IV.A. and IV.B., simulation results will be presented by using PID control technique, as well as by using MPC control technique accordingly.

TABLE I. PHYSICAL MECHANICAL PARAMETERS FOR THE TWO- LINK ROBOTIC MANIPULATOR

Variables and Parameters	Symbols	Values	Uints
Rotational displacement of link1	θ_1	*variable*	degree
Rotational displacement of link2	θ_2	~	degree
Torque of link1	τ_1	~	Nm
Torque of link2	τ_2	~	Nm
Length of link1	L_1	0.2	m
Length of link2	L_2	0.13	m
Mass of link1	m_1	0.41247	kg
Mass of link2	m_2	0.06550	kg
Moment of inertia for motor 1	I_1	0.07143	kg/m^2
Moment of inertia for motor 2	I_2	0.07143	kg/m^2
Acceleration of gravity	g	9.81	m/s^2

A. *Simulation and Results of Using PID Control Technique*

In this subsection, the Simulink model of a two-link robotic manipulator with PID control technique is constructed from the nonlinear model, which already derived in (27) and shown in the Fig. 2 too. Fig. 9 below shows Simulink model used in tuning of PID controllers for the two-link robotic manipulator.

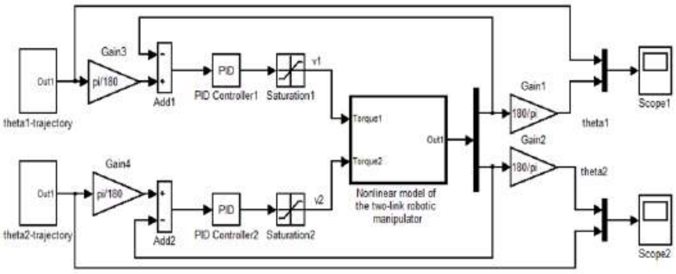

Figure 9. Simulink model of PID controllers tuning for two-link robotic manipulator

The Saturation block in the Simulink model shown above is to constrain the control signals based on the hardware limits. The tuning of control parameters is done manually and the best performance of the controller's parameter values present in the TABLE II. below:

TABLE II. PID CONTROLLER PARAMETER FOR THE TWO-LINK ROBOTIC MANIPULATOR

Controller parameter	Link1	Link2
k_P	50	30
k_I	20	20
k_D	10	5

By running the simulation model of the two-link robotic manipulator shown in the Fig. 9 by using the control parameters as indicated in TABLE II. above, it can be noted at Fig. 10 and Fig. 11 below that every link of the robotic manipulator, follow the desired trajectory superbly but with overshoots or undershoots, at every interaction between the angles of the robot links. The overshoots shown in Fig. 10 and Fig. 11, result from the nonlinearity in the manipulator system, which is clearly shown in the block diagram of its model in Fig. 2. Fig. 12 and Fig. 13 below show the control signals for link1 and link 2 of the robotic manipulator, respectively. As can be seen the control signals v_1 and v_2 reach zero when the links of the robotic manipulator reach their desired trajectories.

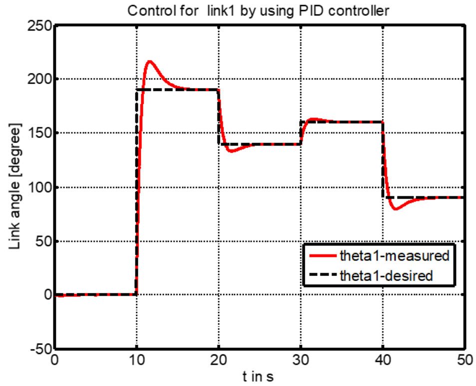

Figure 10. Control for link1 by using PID Controller

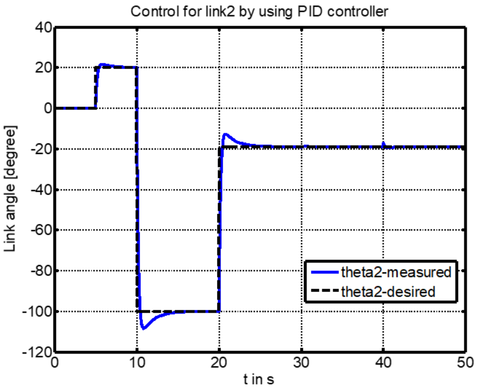

Figure 11. Control for link2 by using PID Controller

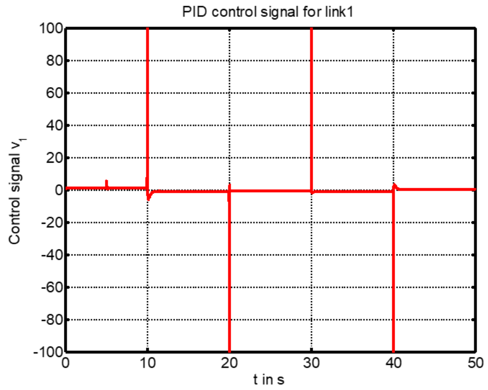

Figure 12. PID Control signal for link1

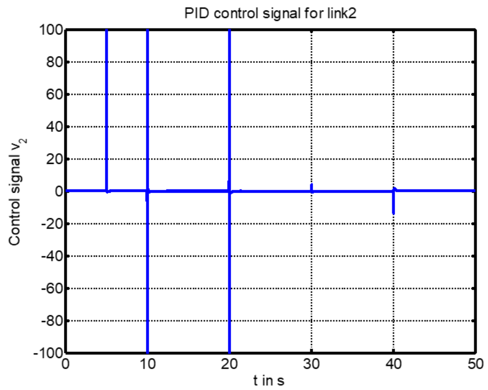

Figure 13. PID Control signal for link2

B. Simulation and Results of Using MPC Control Technique

The Simulink model of a two-link robotic manipulator, controlled with linear MPC controller, has been constructed from subsystems for transformed state space model (feedback linearization analysis), and feedback linearization controller as shown in the Fig. 8 in section III. Fig. 14 below shows a Matlab-Simulink model for model predictive control tuning of the two-link robotic manipulator*:*

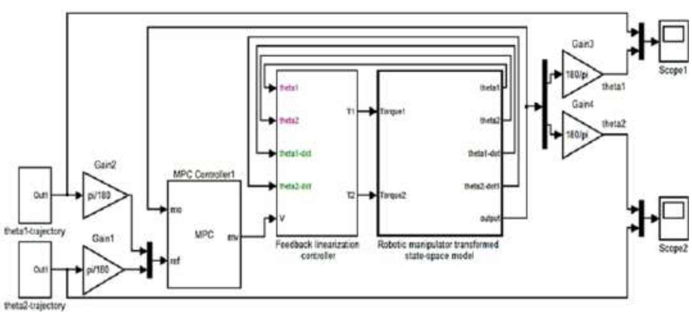

Figure 14. Simulink model for the two-link robotic manipulator controlled using MPC

The MPC controller is designed to follow trajectories of every link of the robotic manipulator. The following TABLE III. shows the MPC parameters that used in the Simulink model of the two- link robotic manipulator system.

TABLE III. MPC CONTROLLER PARAMETERS

MPC parameters	values
Sampling time	0.1 s
Prediction horizon	20
Control horizon	2
Manipulated variables(MVs)	[1,3]
Unmeasured disturbances	[2,4]
Measured outputs	[1,2]
States, inputs, outputs	4,4,2

Fig. 15 and Fig. 16, below demonstrate the convergence of the joint angles θ_1 and θ_2, respectively, to their reference trajectories, using the MPC control technique. It is noticeable that the MPC control approach results in a fast and asymptotic convergence of both joints variables without overshooting or undershooting.

Fig. 17 and Fig. 18 below show the MPC control signals and Fig. 19 and Fig. 20 show the feedback linearization control signals, for link1 and link 2 of the robotic manipulator, respectively. As can be seen the control signals v_1 and v_2 reach zero when the links of the robotic manipulator reach their desired trajectories, the feedback linearization control signals T_1 and T_2 are relatively low energy, which results torques with low energy consumption.

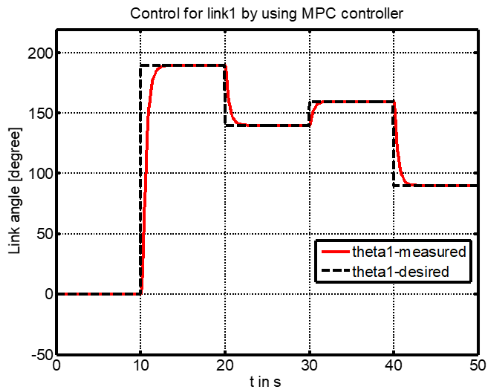

Figure 15. Control for link1 by using MPC Controller

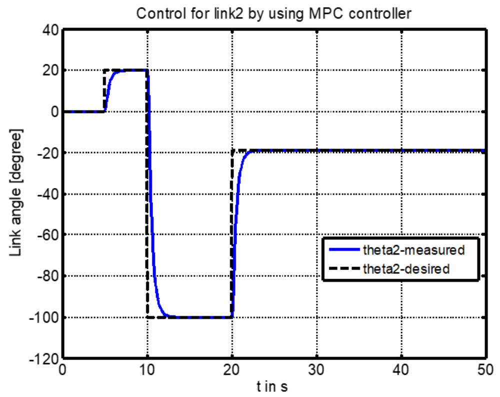

Figure 16. Control for link2 by using MPC Controller

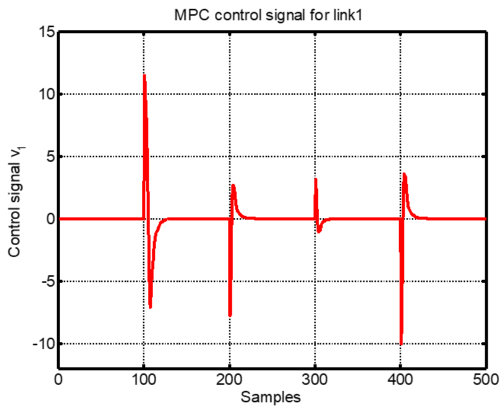

Figure 17. MPC Control signal for link1

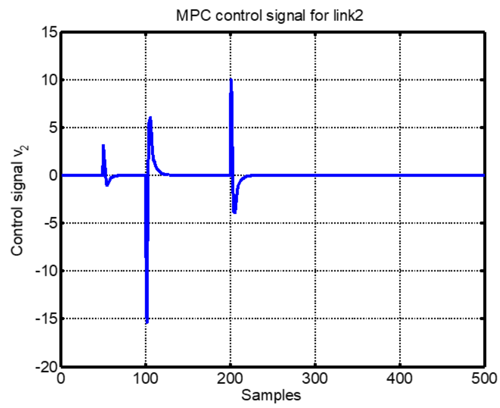

Figure 18. MPC Control signal for link2

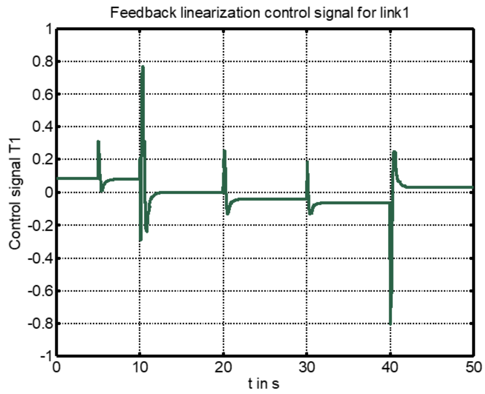

Figure 19. Feedback linearization control signal for link1

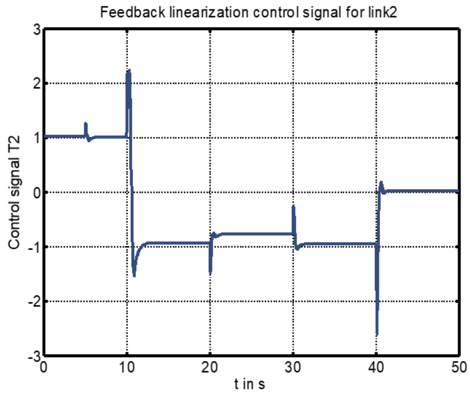

Figure 20. Feedback linearization control signal for link2

VI. Conclusion

In this work, a standard PID control approach was proposed for controlling a two-link robotic manipulator, designed by trial & error method, as well as a novel MPC control approach. The MPC approach starts first by linearizing the nonlinear dynamics of the robotic manipulator. This was achieved by deploying a feedback linearization analysis and control that results an overall feedback control system with linear behavior which can simply be represented by a linear state space model with input disturbances. In another words, the nonlinear dynamics of the two-link arm robot was first controlled by using a primary feedback linearization control loop (feed forward control) to compensate the undesired nonlinear characteristics of the manipulator. Consequently, the resulted overall system can be modelled by a linear model, since the robotic manipulator system behavior became like an ideal linear system. Now, based on the linear model of the feedback linearized system, as a secondary control loop, a model predictive control was developed, and a linear MPC controller was synthetized according to its setup parameters. The PID control system behaved fine but it was with overshoots and undershoots at every interaction between the robot joints. Model predictive control behaved fine without overshoots and undershoots, this is due to that model predictive control (MPC) is capable to consider constraints, on both states and inputs of the system, as mentioned in [24]. The conclusion of this work is that the novel MPC control strategy could perfectly eliminate overshoots and undershoots resulted from the interaction of the robot joints, while the PID control system has failed to eliminate them. So MPC is the go-to option for robotic arms with stringent performance requirements. From the simulation results, we can also conclude that the MPC stategy is ideal for systems with multiple disturbance variables and multiple constraints as by the robotic arm. As for simpler systems with defined dynamics and simple implementation or robotic arms with unstringent performance requirements PID control is sufficient. Furthermore, the experimental application of the real-time MPC control strategy is proposed as future study after the designing and building of a two-degree-of-freedom robotic arm manipulateors.

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التحكم في تتبع المسار للمناول الآلي ثنائي الوصلة باستخدام وحدات التحكم PID وMPC

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الملخص

تناقش هذه الورقة الفرق بين إستراتيجيتي تحكم لغرض تتبع مسار مناور آلي ثنائي الوصلة وتقارن نتائج التتبع للاستراتيجيتين من حيث الدقة ومنع التجاوزات. حيث يعتمد تصميم ومحاكاة أساليب التحكم فيها على تطوير نموذج غير خطي للديناميكيات المعقدة لنظام المناوروتعتمد نمذجة النظام على معادلات أويلر-لاجرانج. الإستراتيجية الأولى هي استراتيجية التحكم بالمشتقات التكاملية التناسبية (PID) و يكون تصميم وضبط المتحكم فيها **(online)** على طريقة التجربة والخطأ، والتي يتم تطبيقها مباشرة للتحكم في مفاصل المناول الآلي. الاستراتيجية الثانية هي استراتيجية التحكم التنبؤي النموذجي (MPC) الجديدة، والتي يعتمد تصميمها على تقنية تحليل بأستخدام التغذية العكسية **(**feedback linearization analysis) والتي تستخدم النموذج غير الخطي لديناميكيات المناور المعقدة لتصميم استراتيجية للتحكم في خطية النظام بأستخدام التغذية العكسية (feedback linearization control) للعمل كحلقة تحكم أولية. ثم استنادا إلى النموذج الخطي الناتج عن التحكم في خطية النظام بأستخدام التغذية العكسية (feedback linearization control)، تم تصميم وتنفيذ وحدة تحكم MPC الخطية و تنفيذها كحلقة تحكم ثانوية. أظهرت نتائج المحاكاة التجريبية، لا سيما من خلال مقارنة الاستجابات الزمنية، أن استراتيجية التحكم التنبؤي MPC لديها أداء يتفوق على استراتيجية التحكم PID ، حيث ظهرت التجاوزات عند استخدام إستراتيجية التحكم PID ولكنها اختفت تماما عند تطبيق إستراتيجية التحكم التنبؤي MPC .

استلمت الورقة بتاريخ ي/ش/س، وقبلت بتاريخ ي/ش/س، ونشرت بتاريخ ي/ش/س

الكلمات المفتاحية:

- التحكم التنبؤي النموذجي
- تحكم المشتقات التكاملية التناسبية
- التحكم في الخطية بالتغدية العكسية
- تحكم التغدية الامامية
- المناور الالي ثنائي الوصلة.

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Asma Eswehli was born in Alkoms /Libya, on January 26, 1983. She received B.Sc. degree in Electrical and Computer Engineering from University of Elmergib, in 2005. She got M.Sc. degree in Process Automation Engineering from Technische Universität Clausthal, /Germany in 2014, where she is currently lecturer in the Department of Electrical and Computer Engineering, Mechatronics Engineering Field at the Faculty of Engineering, Elmergib University, Alkhoms, Libya. Her research field is System Identification and its implementation in mechatronic systems, Kalman filter and its implementations in control engineering, Design, Analysis, Implementation and Control of mechatronic systems and robots.

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