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ITERATIVE LEARNING CONTROL OF A TWO LINK ROBOT ARM

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Abstract

The control of robot manipulators has been an important research subject due to their frequent use in many fields. Meanwhile, learning controllers are widely employed for industrial robots to enable precision control. This paper considers the implementation of Derivative type Iterative Learning Controller (D-type ILC) for trajectory tracking of a two-link robot arm model. The nonlinear mathematical model of the robot is first linearized before applying the ILC controller to the robot system. The controller system is implemented using MATLAB. The results obtained illustrated the efficiency of the proposed controller and are compared to the results of a Proportional-Integral-Derivative (PID) controller.

Keywords: Iterative Learning Control, Two Link Robot Arm, Nonlinear Dynamic Model.

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1. Introduction

Robot manipulators have been an active area of research in the past decades, and it has been widely used in various fields such as industry, education and space exploration [1,2]. Furthermore, robot manipulators provide a great advantage in exploring dangerous or inaccessible environments [3].

One of the fields that robot arms have been increasingly used in recent years is health services. Examples on this are: the use of robotic systems in the rehabilitation of disabled people and robotic surgical systems [4, 5, 6].

Generally, the dynamic model of a robot is found using Lagrange and Euler-Lagrange equations. A robot manipulator is a complex, nonlinear, multivariable system [3], which normally has high parametric uncertainty [7]. These problems are present in two link robot arm and needs to be addressed.

In order to solve these problems involved in the control of robotic manipulators, many studies in the literature have investigated different approaches. Classical linear controllers, like PID, has attracted researchers for decades to use it in industrial robots [8]. However, since the knowledge of a robot system is limited, uncertainty in the parameters and dynamics of a robot model were major challenges that have been considerably explored in the literature. To deal with uncertainty in robotic systems, various controllers were introduced such as robust, adaptive and learning controllers [9]. Examples on using these controllers to address the uncertainty include: the use of adaptive control in [8, 10], robust controller in [11,12] and Lyapunov synthesis in [13].

Moreover, learning controllers are widely used to improve the robotic system performance, by learning from previous executions. For example, in [14], an Adaptive Switching Learning Proportional-Derivative PD controller [ASL-PD] is used for trajectory tracking of a robot manipulator in iterative operation mode.

A well-known example of learning controllers is Iterative Learning Control (ILC). The main area of application of ILC lies in controlling robot manipulators to enable precision in industrial robots [15]. These robots execute a repeated operation over a finite time interval under the same conditions. ILC uses the error information of the previous operation in a system to compute the control action for the next trial. This leads to high performance and low transient tracking error when having large model uncertainty and repeating disturbances in the system. An ILC controller is often used to control a robot that performs a task, reset to its home position and then repeat the task [16].

In the study introduced by Tayebi (2004) [8], an adaptive ILC scheme is presented to control a rigid robot manipulator with unknown parameters. First a Proportional-Derivative feedback control structure is used to stabilize the system and then an ILC is used to deal with the uncertainty in the robot parameters and disturbances.

The work presented in this paper will consider the application of a D-type ILC controller to a two-link rigid manipulator. This controller can solve the problem of parametric uncertainty caused by the nonlinearity in the robot model, ensure fast convergence to the desired input track, and improve the overall performance for the robot arm. To achieve that, the manipulator dynamic model is first linearized, and then D-type ILC is applied to control the linearized model. The results obtained from this approach are compared to the results obtained from applying PID controller to the same model.

The organization of this paper is as follow: Section 2 introduces the two-link robot dynamic model. This model is found using Euler-Lagrange equation. Meanwhile, Section 3 discusses the D-type ILC control design for the robot arm system. In addition, Section 4 presents the simulation and results for the proposed controller. Finally, in Section 5 the conclusions for the work presented in this paper are drawn.

1. Robot Dynamic Model

A two-link robot arm is shown in Figure (1) where θ_i, l_i and m_i are respectively; the joint angle, the link length, and the link mass for the first link ($i = 1$) and the second link ($i = 2$).

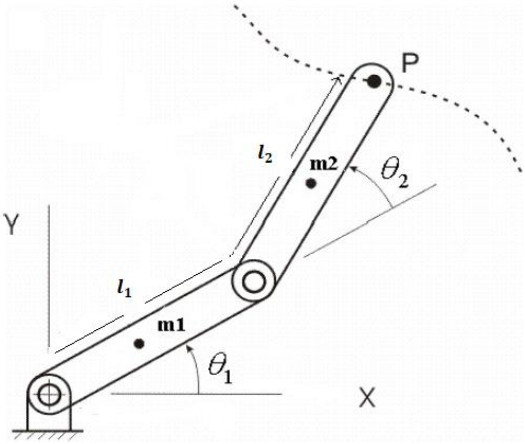


Figure (1) Two-link robot arm.

The dynamic equations for this system can be found using Lagrange Euler formulation. First, we define the Lagrangian L as the difference between the total kinetic energy K and the total potential energy P:

$$L = K - P \qquad (1)$$

Using equation (1), the Euler-Lagrange equation, which is based on the partial derivative of kinetic and potential energies of mechanical systems, is solved to compute the equation of motion as:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \frac{\partial L}{\partial \theta_i} = \tau \qquad (2)$$

where $\tau = [\tau_1 \quad \tau_2]^T$ is the applied torque vector for the robot arm joints, given equation (2), the dynamic model of the two-link robot arm is:

$$M(\theta)\ddot{\theta} + C(\theta, \dot{\theta}) + G(\theta) = \tau, \qquad (3)$$
$$Y = \theta.$$

Where Y is the output vector, g is the gravitational force, and:

$G(\theta) = \begin{bmatrix} (\frac{1}{2}m_1 + m_2)g\,l_1\cos\theta_1 + \frac{1}{2}m_2 g\,l_2\cos(\theta_1 + \theta_2) \\ \frac{1}{2}m_2 g l_2\cos(\theta_1 + \theta_2) \end{bmatrix}$ is the gravity torques vector;

$C(\theta, \dot{\theta}) = \begin{bmatrix} -m_2\,l_1 l_2 \sin\theta_2\,\dot{\theta}_1\dot{\theta}_2 - \frac{1}{2}m_2 l_1 l_2 \sin\theta_2\dot{\theta}_2^2 \\ \frac{1}{2}m_2 l_1 l_2 \sin\theta_2\dot{\theta}_1^2 \end{bmatrix}$ is the Coriolis and centrifugal forces vector;

$M(\theta) = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$ is the inertia matrix, where:

$$M_{11} = \left[\left(\frac{1}{3}m_1 + m_2\right)l_1^2 + \frac{1}{3}m_2 l_2^2 + m_2 l_1\,l_2\cos(\theta_2)\right]$$

$$M_{12} = M_{21} = m_2\left[\frac{1}{3}l_2^2 + \frac{1}{2}l_1 l_2\cos(\theta_2)\right]$$

$$M_{22} = \frac{1}{3}m_2 l_2^2$$

2. ILC Controller Design

As explained earlier ILC was originally developed to enable precision control of industrial robots. The first learning control scheme proposed by Arimoto, et. al (1984) [17] involved the derivative of the error $\dot{e}_k(t)$ for the D-type ILC controller. This derivation is given in the following equations:

$$\dot{e}_k(t) = de_k/dt \qquad (4)$$

$$e_k(t) = y_{ref}(t) - y_k(t) \quad (5)$$
$$y_k(t) = g(t)u_k(t) \quad (6)$$
$$u_{k+1}(t) = u_k(t) + L * \dot{e}_k(t) \quad (7)$$

Where $g(t)$ is the plant and it is required that the output signal y_k repeatedly tracks a reference signal y_{ref} which is T seconds long. The subscript k is the trial number and it has a positive value ($k > 0$). Tracking error signal $e_k(t)$ control the input signals $u_k(t)$ and the input for the next trajectory $u_{k+1}(t)$. Finally, L is the learning factor. In this setting, the ILC controller tracks a fixed reference input over a finite interval of T seconds.

Figure (2) shows our proposed approach of ILC setup for robotic arm system. In this system, it is required that the output signal of the system (y_{1k} and y_{2k}) repeatedly tracks the reference signal y_{ref1} and y_{ref2} respectively, which is T seconds long, where the subscript k is the trial number and $k > 0$.

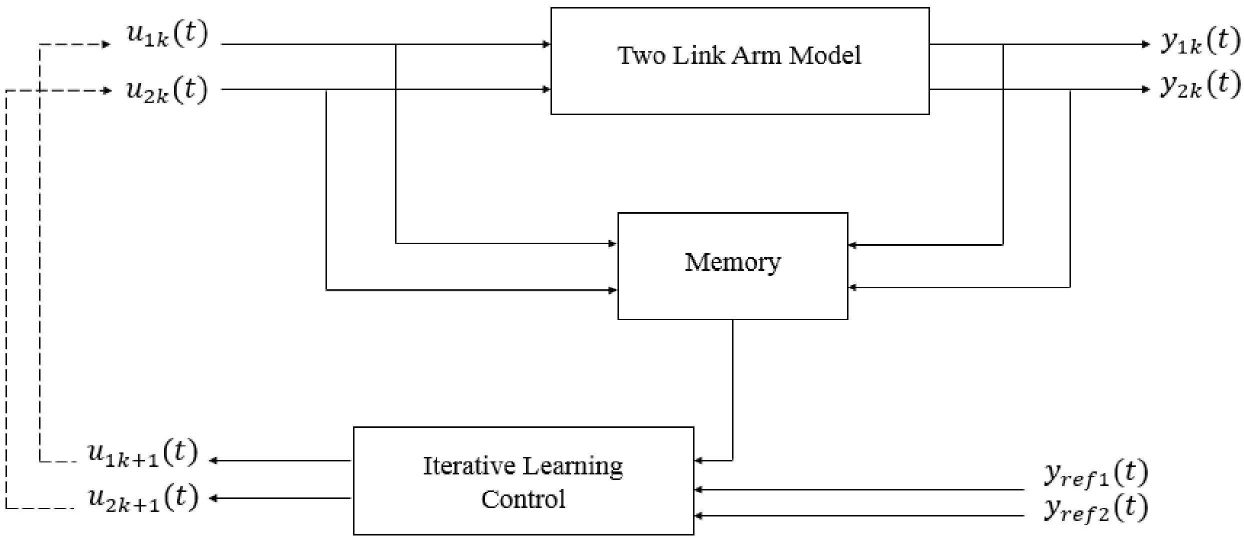


Figure (2) ILC control system for two link arm model.

The proposed system defines the ILC controller scheme using equations (4-7). Meanwhile, the two-link arm robot model is found using equation (3) defined in Section (2). Here, let the mass of links $m_1 = m_2 = 1\text{kg}$, the length of the links $l_1 = l_2 = 0.3\text{m}$, the gravity $g = 9.8\,\text{m/s}^2$. Next, we linearize the arm model, and let us assume that:

$$\theta_1 = x_1 \,,\ \theta_2 = x_2 \ ,\ \dot{\theta}_1 = x_3 \ ,\ \dot{\theta}_2 = x_4.$$

We can write the two-link arm state space model as:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -112.11 & 70.07 & -2.79 & 1.54 \\ 280.28 & -224.22 & 7.75 & -4.64 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 19.04 & -47.61 \\ -47.61 & 152.38 \end{bmatrix} \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$

The linearized robot system is a stable system with high overshoot and setting time which is equal to 35.1s and steady state error which is equal to 83% for link 1, and a setting time which is equal to 28s and steady state error which is equal to 32% for link 2.

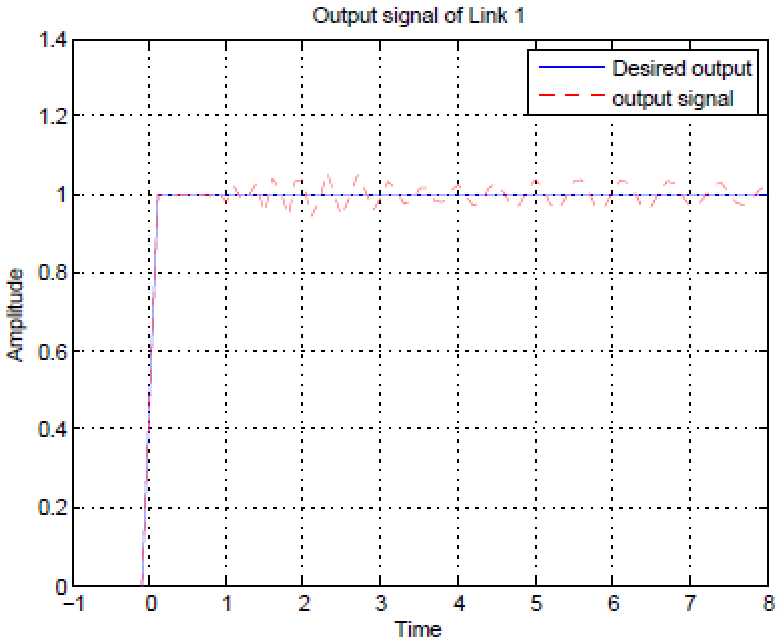
3. Simulation and Results

In this section, the control system shown in Figure (2) in which the D-type ILC in equations (4-7) is applied to the robot system given in equation (8). The implemented of this system was carried out in

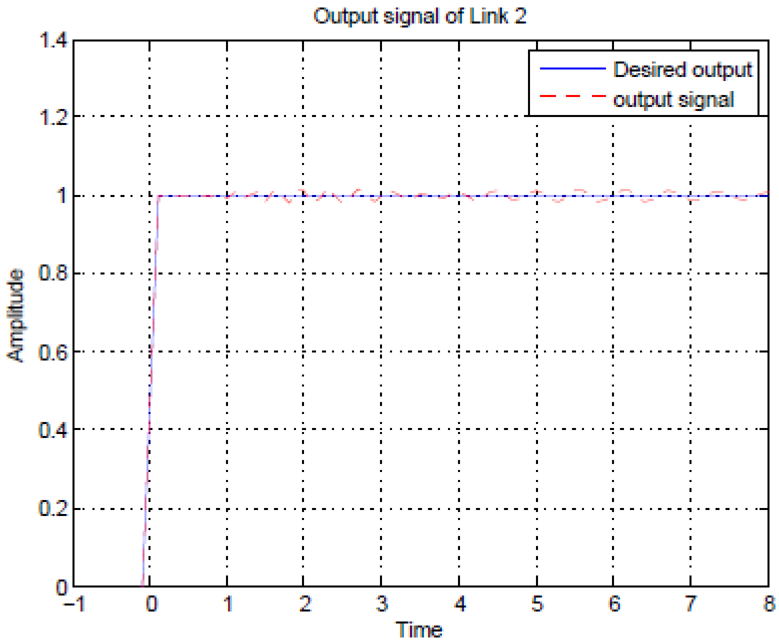
MATLAB. The pseudocode for the application of the ILC to the robot arm presented in this work is given below:

- Initialise count to zero
- Initialise vector time T to be in the range (0,8) with a 0.1 step size
- Set the input signal to step input
- Define the state space for the model
- Process (1):
- **For** i =1 to number of iterations
  - Find the actual system output
  - Find the error between the actual output and the desired output
  - Compute the differentiation of the error signal for link 1 and link 2 of the robot arm
  - Find the max(error)
  - **If** max(error) <0.05 **then**
    - Break
  - **Else**
    - compute the new input signal=old input + learning factor * the derivative of the error signal
    - **End if**
  - Increase count by 1 and repeat Process (1)
- **End for**
- plot the output signal for link 1 and link 2 of the robot arm

On the other hand, Figure (3a) and Figure (3b) shows the output for link 1 and link 2.



(a)



(b)

Figure (3) D-type ILC control for two link robot arm (a) Transient response for link 1 (b) Transient response for link 2.

The simulation illustrates that a D-type ILC applied to the robot arm system can effectively give a full tracking of the desired input signal for a period of 8 seconds with zero steady state error. These results were compared to the results of applying PID controller to the robot system with ($k_p = 0, k_i = 0.201, k_d = 0$) for link1 and ($k_p = 0, k_i = 0.0878, k_d = 0$) for link2. In this case, the setting time for link 1 was found to be equal to (114.6) and the setting time for link 2 was found to be equal to (65.5) with zero steady state error. This shows that ILC has improved performance with very fast convergence compared to applying PID controller.

4. Conclusions

In this work, a two-link robot manipulator was considered. The mathematical model for this system was derived using Euler-Lagrange equation. The nonlinear model of the robot was linearized and then a D-type ILC controller was applied to the linear model of the robot arm system. The results showed that the ILC controller had succeeded in making the robot arm fully track the desired input signal with the convergence of the tracking error to zero value. The results for the implemented ILC control system was compared to a classic PID controller to show the effectiveness of the ILC controller. It was found that the proposed ILC control system can achieve fast convergence and improve the overall performance compared to PID controller.

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