“Hardware realization and PID control of multi-degree of freedom articulated robotic arm

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Hardware Realization and PID Control of Multi-Degree of Freedom Articulated Robotic Arm

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Abstract . A robotic manipulator is the most important component in an industrial environment for autonomous execution of tasks. Given the repoted fact that a Proportional-Integral-Derivative (PID) will continue to be the main workhorse in the automation sector, the present paper deals with designing and realizing this control law. A custom-developed pseudo-industrial platform AUTonomous Articulated Robotic Educational Platform (AUTAREP) centered on a 6 DOF manipulator is considered. The derived kinematic and dynamic models of the arm form the basis of MATLAB-based control simulation. The control law after discretization is also implemented on embedded hardware. When subject to various inputs, result of trajectory tracking in the form of output responses, demonstrate superior performance in transient as well as steady state. The stability and convergent behavior of the outputs is also observed, thus highlighting efficacy of proposed approach.

Keywords: Robot control, PID, Serial robotic arm.

1 Introduction

Progress in the field of science and technology has brought the idea of industrial automation. In 1940, Ford Motor Company first time used the word automation for the collective operation of interconnected machines [1]. At present, the concept of automation is described as automatic control of production lines to save physical and mental labor. Recent advancements in the research have introduced robots in production processes which represent the utmost form of automation. The robots offer wide range of advantages like safety, precision, swiftness and efficiency. Moreover they can work in hazardous and inhospitable environments where human interaction is cumbersome or even impossible. Essentially, safety is still a grave concern, which demands careful consideration for many robots used in industry as well as in other applications. Today, robotic arms find their applications in many industrial processes like welding [2], cutting [3], packaging [4], spraying [5] etc. Additionally, they facilitate the tasks accomplished in various fields including but not limited to: medical [6, 7], space exploration [8], nuclear plants [9] and so on.

The design of a robot involves its mathematical modeling followed by controller design. Control of a robotic arm deals with the problem of formulating the joint angles required to move end-effector to follow a certain specified trajectory. An optimal control technique offers highly precise performance of the arm. Various control strategies have been discussed in the literature for this purpose. Robot dynamics based control has been formulated by Khatib [10]. Energy reshaping and damping injection method has been used in [11] to control the motion of the robot. Other techniques to control motion of the robot can be based on positioning [12], inverse Jacobian [13] or hybrid combination of neural networks and $H\infty$ [14].

The complex computation and the exact information of the robot model are the main disadvantages of such control techniques [15]. Despite their robustness and disturbance handling capability, these strategies are seldom employed in industrial scenarios. In contrast, Proportional-Integral-Derivative (PID) control is the most dominant feedback control technique for industry [16] because of its inherent simple structure and physical meaning of parameters [17]. It serves as a flexible method to control the system autonomously [18]. Parameter tuning of PID is comparatively easy, especially for robots with gear or belt power transmission system [19]. Such systems increase the torque or force significantly and enhance the ability of actuators to drive even large masses.

Despite the fact that manipulator control has been thoroughly investigated in research community, most of the reported works are limited to simulation. In this paper, PID controller has been designed and implemented on a 6 Degree Of Freedom (DOF) pseudo-industrial robotic arm to improve its response in term of overshoot, settling time and steady-state error. The arm is a central component of AUTonomous Articulated Robotic Educational Platform (AUTAREP) proposed by researchers at COMSATS institute [20]. Figure 1 illustrates the arm together with other components of AUTAREP. It is a serial link robotic arm with 5 revolute joints including base, shoulder, elbow, wrist and tool. The actuation system consists of precise servomotors (DME38B50G-115 for joints and DME331337G-171 for gripper) equipped with optical encoders for position feedback. Other on-board sensors include a Force Sensing Resistor (FSR) to permit tactile differentiation of object's stiffness and a camera for providing vision to the robot. Finite time stability of the system is demonstrated in simulation as well as through hardware implementation. The kinematic and dynamic models of the arm are derived to simulate the proposed controller. The controller is then realized physically based on custom developed embedded hardware.

The paper is organized as follow: Mathematical modeling of the arm is presented in Section 2. Section 3 discusses the controller design followed by the simulation results while Section 4 details the electronics of the custom-developed hardware and the results of the proposed controller realized on the hardware. Finally, Section 5 comments on conclusion and future work.

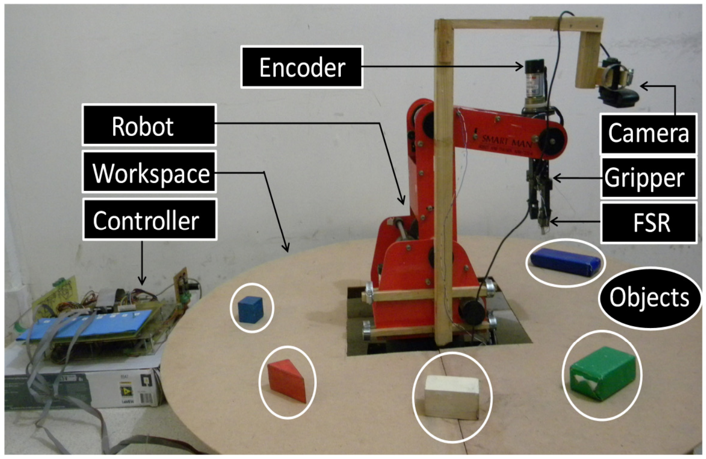


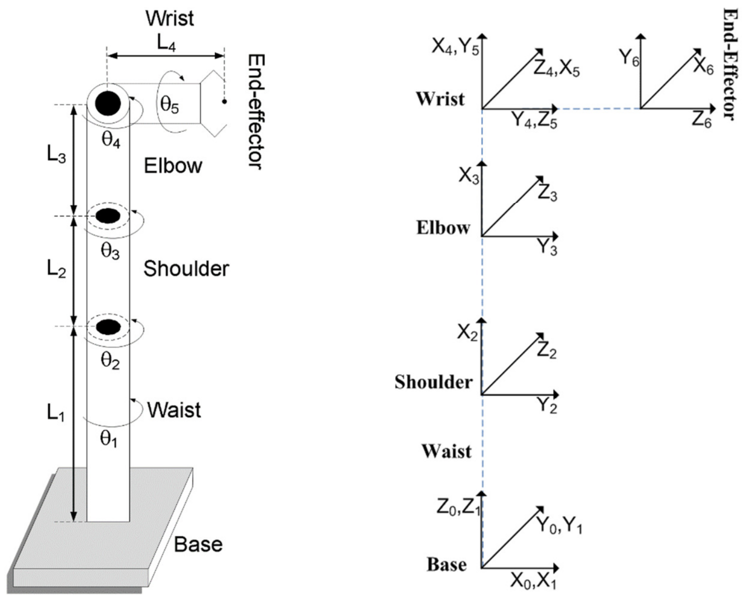
Fig. 1. AUTAREP – An educational platform with diverse range of sensory and actuation capabilities

2 Robot Modelling

Robot modeling involves the computation of its kinematics and dynamics. Kinematics is the study of relationship between robot's joint angles and resulting position of links and end-effector [21]. It can be formulated by using Denavit-Hartenberg (DH) parameters, Lie Algebra method, Hayati-Roberts (H-R) representation and screw theory. A comprehensive review of these approached has been presented by Ajwad et al. in [22]. Kinematic analysis consists of Forward Kinematics (FK) and Inverse Kinematics (IK). Computation of end-effector coordinates from the given joint angles is FK while required joint angles for a desired orientation and position of end-effector can be determined through IK.

The present research uses DH parameters representation to derive the kinematic model of the robot because of systematic nature and versatility of this representation to model any number of links and joints of a serial manipulator. Figure 2a illustrates the schematic of the arm at its home position while frame assignment to each joint is shown in Fig. 2b. Wrist joint, actuated in 2 DOF (roll and pitch) has been presented with two frames.

Transformation matrices of each link have been derived by using general form of transformation matrix in which joint i is expressed in its neighboring joint i-1 [23]. The overall transformation matrix (1), representing end-effector pose into base, is then obtained by using compound transformation property. Detailed FK and IK models of the arm have been presented in [24].



(a) (b)

Fig. 2. Kinematic modeling (a) Home position (b) Frames assignment

$$ {}^{0}_{6}T = \begin{bmatrix} C_1C_5S_{234} + S_1S_5 & -C_1S_{234}S_5 + S_1C_5 & C_1C_{234} & C_1A \\ -S_1C_5C_{234} - C_1S_5 & S_1C_{234}C_5 + C_1C_5 & S_1C_{234} & S_1A \\ C_{234}C_5 & -C_{234}S_5 & -S_{234} & B \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

where

A = $L_2\, S_2 + L_3\, S_{23} + L_4 C_{234}$

B = $L_1 + L_2\, C_2 + L_3\, C_{23} - L_4\, S_{234}$.

Nomenclature used in (1) is given below:

$C_{\alpha\beta} = \cos(\alpha + \beta)$

$C_{\alpha\beta\gamma} = \cos(\alpha + \beta + \gamma)$

The dynamic model of a robot provides relationship between its motion and forces causing the motion [25]. It can be derived by using recursive Newton-Euler [26], recursive Lagrange [27] and Euler-Lagrange [28] approaches etc. Dynamic model of the AUTAREP arm has been derived using Euler-Lagrange method.

$$ \tau = M(q)\ddot{q} + V(q, \dot{q}) + G(q) \quad (2) $$

where τ represents input torque. $V(q,\dot{q}) \in \Re^{4\times1}$, $G(q) \in \Re^{4\times1}$ and $\ddot{q} \in \Re^{4\times1}$ denote force matrices accounting for Corollis and Centrifugal forces, gravity matrix and acceleration, respectively. $M(q) \in \Re^{4\times4}$ is the inertia matrix given by (3).

$$M(q) = M_\omega(q) + M_v(q) \tag{3}$$

$M_\omega(q)$ and $M_v(q)$ are the inertia matrices due to angular velocities and linear velocities given by (4) and (5) respectively.

$$M_\omega = \begin{bmatrix} M_{11} & 0 & 0 & 0 \\ 0 & M_{22} & M_{23} & M_{24} \\ 0 & M_{32} & M_{33} & M_{34} \\ 0 & M_{42} & M_{43} & M_{44} \end{bmatrix} \tag{4}$$

$M_{11} = am_1 + (c+b)(m_2+m_3) + em_4$ $\quad M_{22} = d(m_2+m_3) + km_4$

$M_{23}, M_{32} = dm_3 + km_4$ $\quad M_{24}, M_{42} = km_4$

$M_{33} = dm_3 + km_4$ $\quad M_{44}, M_{34}, M_{43} = km_4$

$$M_v = \begin{bmatrix} m_{11} & 0 & 0 & 0 \\ 0 & m_{22} & m_{23} & m_{24} \\ 0 & m_{32} & m_{33} & m_{34} \\ 0 & m_{42} & m_{43} & m_{44} \end{bmatrix} \tag{5}$$

$m_{11} = (m_2+m_3+m_4){c_2}^2{l_2}^2 + (m_3+m_4)({l_3}^2{c_{23}}^2 + 2l_2l_3c_2c_{23}) + m_4({l_4}^2{s_{234}}^2 - 2l_2l_4c_2s_{234} - 2l_3l_4c_{23}s_{234})$

$m_{22} = (m_2+m_3+m_4){l_2}^2 + (m_3+m_4)({l_3}^2 + 2l_2l_3c_3) + m_4({l_4}^2 - 2l_2l_4s_{34} - 2l_3l_4s_4)$

$m_{23}, m_{32} = (m_3+m_4)({l_3}^2 + l_2l_3c_3) + m_4({l_4}^2 - l_2l_4s_{34} - 2l_3l_4s_4)$

$m_{24}, m_{42} = m_4({l_4}^2 - l_2l_4s_{34})$

$m_{33} = (m_3+m_4){l_3}^2 + m_4({l_4}^2 - 2l_3l_4s_4)$

$m_{34}, m_{43} = m_4({l_4}^2 - l_3l_4s_4)$

$m_{44} = m_4{l_4}^2$

where m_1, m_2, m_3 and m_4 represent the mass of each link while l_1, l_2, l_3 and l_4 represent their lengths. a, b, c ,d, e, k are the constants whose values have been computed based on the Inertia matrices of each link. The detailed derivation of dynamic model including the matrices V(q,q̇) and G(q) has been presented in [29].

3 Controller Design and Simulation

PID provides efficient and computational inexpensive solution for most of the industrial applications. In the nonlinear dynamic equation (2), the input torque τ is unknown. PID law has been used to design appropriate control input that ensures stability. The controller can be described by the differential equation (6).

$$\tau = K_p e + K_d \dot{e} + K_i \int e \text{ dt} \tag{6}$$

where $e = q_d - q$ is 4x1 error matrix and q_d is the desired joint position. K_p, K_d and K_i are proportional, derivative and integral gains, respectively and can be defined as:

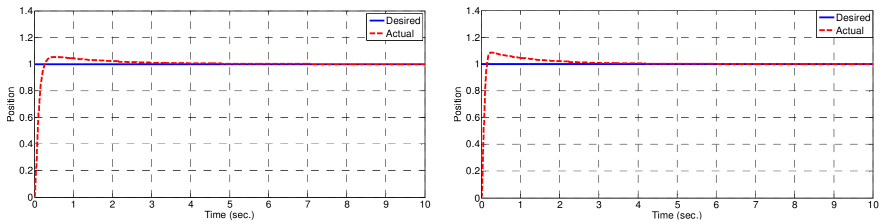
$$K_p = diag\{K_{p1}, K_{p2}, K_{p3}, K_{p4}\}$$
$$K_d = diag\{K_{d1}, K_{d2}, K_{d3}, K_{d4}\}$$
$$K_i = diag\{K_{i1}, K_{i2}, K_{i3}, K_{i4}\}$$

where the four sub-gains refer to the first four joints of the arm. The closed-loop system is obtained by replacing control input τ (6) in the robot model (2).

$$K_p e + K_d \dot{e} + K_i \int e = M(q)\ddot{q} + V(q, \dot{q}) + G(q) \tag{7}$$

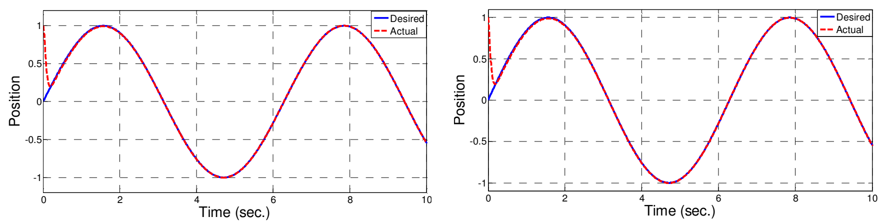
$$\ddot{q} = M^{-1}(q)[-V(q, \dot{q}) - G(q) + K_p e + K_d \dot{e} + K_i \int e \, dt] \tag{8}$$

Eq. (8) is basically state equation of the closed loop system where PID part represents the system input. The output is acceleration from which other states i.e. position and velocity, are computed. Based on the derived control law, simulations have been carried in MATLAB/Simulink 2009 to study and investigate tracking problem of the control. The control has been subjected to various inputs including step, sinusoidal and ramp with initial states taken 0, 1 and 3 respectively. Corresponding responses for various joints are illustrated in Fig. 3-5 respectively. There is no effect of nonlinearities in (8) since the control input is solely based on the position error terms. Step response is presented for the first two links of the robots while sinusoidal response is plotted for the last two links. Ramp response is given for elbow and wrist joints. Results clearly demonstrate the finite time stability of the system. Peak time in all the three cases is less than 1 sec as can be seen in responses plots. About 5% overshoot is observed in step response while in sinusoidal response there is no overshoot/undershoot. Settling time is within acceptable range for step and ramp responses. In case of sinusoidal response, once actual position reaches the desired trajectory, it then follows it for the rest of the time.



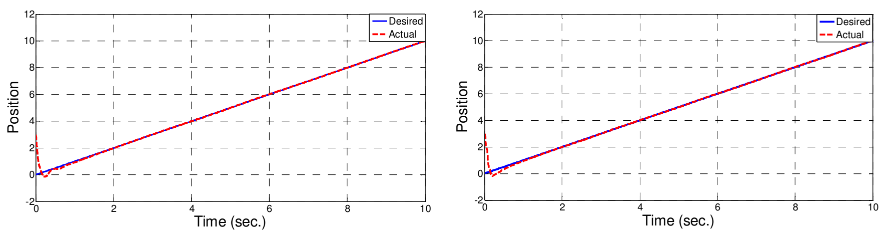
(a) (b)

Fig. 3. Step response of (a) Base joint (b) Shoulder joint



(a) (b)

Fig. 4. Sinusoidal response of (a) Shoulder joint (b) Elbow joint



(a) (b)

Fig. 5. Ramp response of (a) Elbow joint (b) Wrist joint

4 Controller Implementation

The proposed embedded hardware is centered on a 16-bit digital signal processing controller dsPIC33FJ256GP710A. The state feedback of each joint of the robot including its direction and position information is provided to the central microcontroller using differential optical encoders mounted on the joint's motor. The controller can be operated through GUI software installed in a PC/laptop or a teaching pendent. An intuitive instruction set comprising of more than 100 kernel commands has been designed to facilitate controller implementation over the hardware. The controller communicates with the GUI through UART while digital input ports provide an interface between teaching pendent and the controller. Figure 6 presents the architectural design of the embedded controller, where for simplicity only a single DC servo motor and optical encoder is shown with a motor driver. The overall system consists of six motors controlled by a single Micro Controller Unit (MCU).

Desired speed of the motors can be controlled with a 16-bit timer module of MCU by generating Pulse Width Modulation (PWM) of respective duty cycle. The pendent is interfaced with Change Notification (CN) interrupt digital I/O pins. Current sensing resistors are added to each motor driver to limit current supply in case of motor stall, to avoid damage to mechanical structure of the Arm. Current sensors are interfaced to internal Analog to Digital Converter (ADC) unit of MCU. A current and home position of all motors is recorded in E^2PROM of MCU. The motors draw current of 0.65A in normal working operation and 1.5A in stall condition. These figures are incorporated while designing a custom motor driver using BJT switches. Fabricated hardware is presented in Fig. 7.

For hardware implementation, differential equation of the control law is converted into difference equation using Euler's technique, which is based on differentiation written in (9).

$$\dot{z} = \lim_{\delta t \to 0} \frac{\delta z}{\delta t} \tag{9}$$

where δ represents a small change and can be approximated in digital domain as (10).

$$\dot{z}(k) \cong \frac{z(k) - z(k-1)}{T} \tag{10}$$

where T is sampling time, $z(k)$ and $z(k-1)$ are the present and current values respectively. The integration is also approximated in microcontroller by summing up all the previous values. Subject to various inputs, Fig. 8-10 illustrate the step, sinusoidal and ramp responses for various joints. It can be seen that transient as well as steady state parameters are in acceptable range.

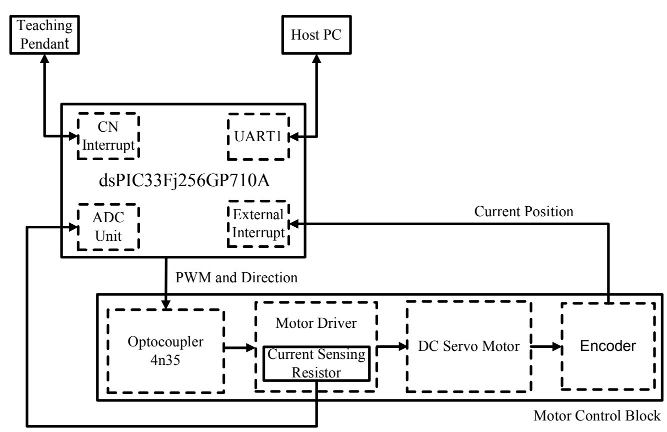


Fig. 6. Block diagram of embedded hardware for position control

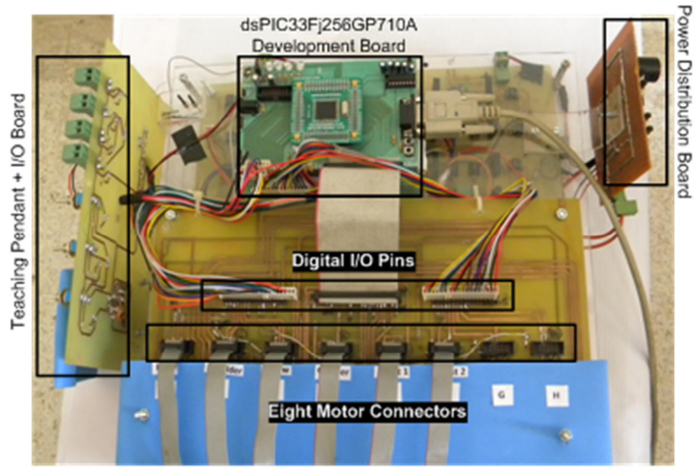


Fig. 7. Fabricated hardware

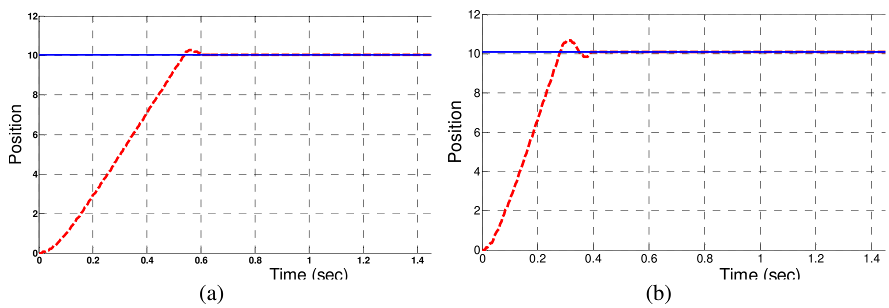


Fig. 8. Step response of (a) Base joint (b) Shoulder joint

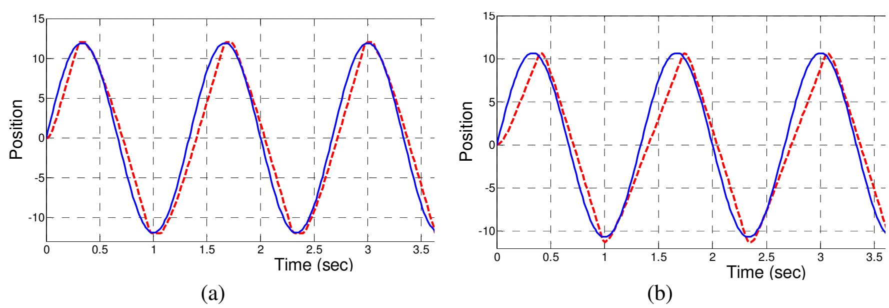
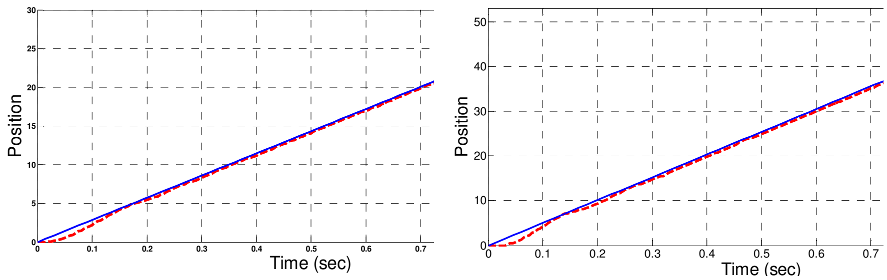


Fig. 9. Sinusoidal response of (a) Shoulder joint (b) Elbow joint



(a) (b)

Fig. 10. Ramp response of (a) Elbow joint (b) Wrist joint

5 Conclusion

This research models a 6 DOF robotic arm and then designs and implements a PID control law. MATLAB based simulations have been carried out based on the dynamic model of the arm. Moreover the discretized controller has also been implemented on real hardware to observe its performance in actual working environment. The system response has been recorded for various inputs (step, sine and ramp). Both simulation and hardware results witness that the proposed control law has the capability to track almost any kind of input trajectories. The transient parameters including peak time, settling time, %overshoot etc. as well as steady state error have been observed to be within limits as expected. In future, it is planned to improve PID law by hybridizing it with other robust and adaptive control strategies as respectively reviewed in [30] and [31].

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