Implementation of a New PC based Controller for a PUMA Robot based on COEM

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Abstract—**The Controller Output Error Method (COEM) is introduced and applied to the design of an adaptive fuzzy controller for a PUMA robot. The method employs a gradient decent algorithm to minimize a cost function which is based on the error at the controller output. The cost function is minimized by adapting some or all of the parameters of the fuzzy controller. The paper also describes the replacement of a controller for a PUMA 512 robot with a newly designed PC based (open architecture) controller employing COEM. The original structure of the PUMA robot is retained. The hardware of the new controller includes in-house designed parts as: PWM amplifiers; digital and analog controllers; I/O cards; signal conditioner cards; and 16 bits A/D and D/A boards. An Intel Pentium IV industrial computer is used as the central controller. The control software has been implemented using VC++ programming language. The trajectory tracking performance of all the six joints was tested at varying velocities. The experimental results showed that it is feasible to implement the suggested open architecture platform for PUMA 500 Series robots through software routines running on a PC.**

Index Terms—**PUMA robot, Adaptive fuzzy control, Pulse width modulation (PWM) amplifier, Graphical user Interface (GUI), Controller output error method (COEM).**

I. Introduction

Robots form an essential part of mechatronics and Computer Integrated Manufacturing (CIM) systems. Robots are generally controlled by dedicated controllers. As upgrades become costly and interfacing becomes complex due to hardware and software conflicts, the flexibility of the robotic manipulators is reduced. Dedicated hardware and proprietary software which normally allows only high level programming by the users are costly and difficult to understand.

Since the early years of 1980's many projects have been carried out to develop an open architecture controller such as NGC[1], GISC[2], ROBLINE[3] and so on which try to solve the problem of realization of an open architecture controller, and several prototype systems have been developed. However, they are not widely accepted due to the overly restrictive definitions and special standards.

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The Unimate PUMA 500 series Robots mainly uses DEC LSI 11 processor running VAL robot control software[4]. Methods of bypassing VAL are discussed in literature, including Unimation technical reports[5]. However, most of these procedures have been confined to replacing the LSI 11 with another DEC computer, leaving peripheral hardware intact. A well- refined open structure architecture for industrial robot is discussed in [6]. However; it is mainly based on Common Object Request Broker Architecture (COBRA), leaving scope to simplify the hardware and software work. A hardware retrofit for Puma 560 robot is discussed in [7] but still it relies on special-purpose TRC041 cards installed on the backplane of Mark II controller.

The shift towards the personal computer open architecture robot controller and the impact of using these newer controllers for system integration is discussed in [8]. In fact; it is far more cost effective to develop new hardware using less specific interfaces. An improved PC-based design for Puma robot was presented in [9] but this hardware configuration purely depends on in-house built designs. In our paper a flexible, modular hardware is developed for the puma robot, incorporating a personal computer, in-house as well as specialized hardware. Some technical problems in the previous design for velocity test profile of joints1, 2 and 4 have also been addressed. The joints position tracking error at high velocities is also minimized in our design.

In this paper, an adaptive *fuzzy* control design is developed for robot trajectory tracking control. The controller output error method (COEM) is introduced in proposed design, which can be used for the on-line tuning of parameters of a fuzzy controller. This method can be used with any fuzzy controller design; the only requirement is that controller must be stable before the commencement of on-line tuning. Thus, at first, any fuzzy rule-based model and any inference mechanism can be employed to parameterize and initialize controller *of* the system, and then COEM is applied subsequently to tune parameters of fuzzy controller for purpose of achieving better performance Although the method has already been discussed by few authors[10, 11] but its implementation for a PUMA robot using an open architecture platform was not studied so far. The authors employ the adaptive fuzzy control using COEM method as a control strategy to implement the open architecture design for PUMA 560 robot.

II. Original PUMA Unimate 500

The Unimation Mark II is an industrial robot controller as shown as in Fig.1. It consists of mainly a DEC LS1 serial

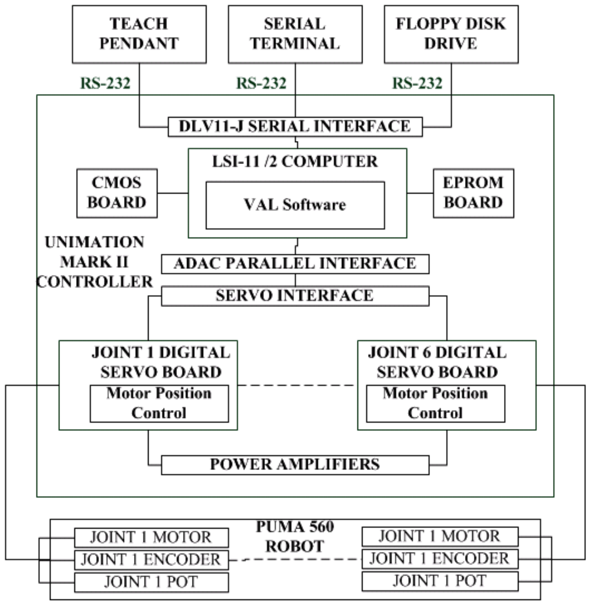

Fig.1 Unimate Puma 512 block diagram

interface board; CMOS board and EPROM board; servo interface board and Six digital servo boards [12].

The original system used a large number of operational amplifiers and discrete components for conditioning of shaft encoder signals and amplification of analog control voltages. This leaves considerable scope to simplify and compact the controller design by substitution of more modern components.

III. NEW HARDWARE CONFIGURATION

The PUMA 512 robot used for work is described in Fig.2. It is a member of the Unimate 560 series of Robots, having six joints.

Each of PUMA 512 joints is driven by through a gear train by a permanent magnet DC servo motor which incorporates a rotary shaft encoder, a tachometer and a potentiometer. The new system's block diagram is shown in the Fig.3. The PWM amplifier box contains 6 in- house built amplifiers employing SA01. The SA01 amplifier is a pulse width modulation amplifier that can supply 2KW to the load.

The control box includes an internally designed digital conditioner card for shaft encoder's signals and an analog conditioner card for potentiometer and tachometer. The in-house built encoder conditioner card uses ALTERA MAX 7256AETC100-10 CPLD [13]. It belongs to MAX 7000A programmable device family. The card has 3 CPLDs one for each shaft encoder

The robotic arm needs two digital conditioner cards. The CPLDs are programmed using VHDL language. The signals A+, A-, B+, B-, Z+ and Z-, VCC and DGND are the eight signals from rotary shaft encoder which are interfaced to the CPLD via a differential line receiver MC3486. The 24 signals D0_waist to D23_waist go to 6 channels 722 DIO card. The other 5 joints' shaft encoders are connected to digital conditioner card in the same way. The power supply

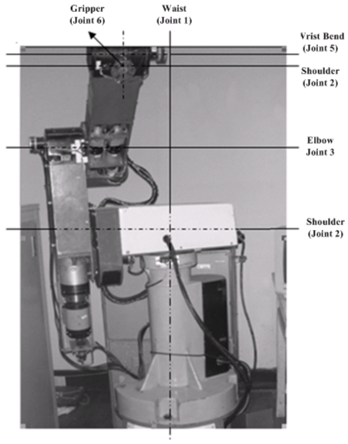

Fig.2 PUMA robot 512 joints identification

unit incorporates power supplies for PWM amplifiers units, signal conditioner cards and an excitation 110V power supply for 6 servo motors.

A Pentium IV industrial computer is used as a central controller. It has one 6 channel 722 DIO card, 16 bits 816 A/D and 6126 D/A cards.

The analog signals from tachometers and potentiometers are fed into the analog conditioner card. The card was designed at Simulation & Machine Control lab (S & MC). After conditioning the signals, they are fed to industrial PC (A/D card). The analog feedback signals from D/A are provided to PWM amplifiers for each joint to complete the speed loop.

A. *Advantages of new PC based PUMA robot*

A new PC-based PUMA robot manipulator control system has three advantages: simplicity, flexibility and low cost. The hardware and software complexity of the Unimate Mark II robot controller is extensively reduced as discussed in section 3. Flexibility refers to the ability to implement arbitrary control strategies which can easily integrate sensor information into low level control. Flexibility also refers to the ability to easily use wide variety of sensors in the trajectory generator. The suggested PC based platform has the ability to easily integrate such sensors as sonars, ranging lasers, cameras etc. that would allow the user to implement complex control strategies (e.g. vision based control). With the current digital servo boards in the Mark II, none of these advanced modes are feasible.

Another potential advantage of the suggested platform is its cost effectiveness. Due to economies of scale and increased CPU power, personal computers have become viable and cost effective alternatives to workstations in engineering applications. An Intel processor easily outperforms a Spark IPX while costs less than a thousand dollars.

IV. DESCRIPTION OF THE CONTROL SCHEME

A. *Manipulator dynamic model*

The dynamic model of an n-link manipulator is given as [14]:

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

Where q is the n dimensional joint variable, $\dot{q}$ is the time derivative of q, i.e. velocity, M(q) is the n × n inertia matrix, $C(q,\dot{q})\dot{q}$ is the n-dimensional vector of coriolis and centrifugal force, G(q) is the n-dimensional vector of gravity force and τ is the n dimensional vector of applied torque.

After taking the effects of random disturbances into account, the manipulator dynamic model becomes as under:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + B_d(q,\dot{q}) = \tau \qquad (2)$$

Where $B_d(q,\dot{q})$ represents an additive bounded disturbance due to load variation and modeling errors.

A. The Controller Output Error Method

The Controller output error method is a technique of fine tuning the parameters of a fuzzy system within the control architecture shown in Fig.4.COEM is a strategy for adapting the parameters of a controller without the use of an implicit or explicit plant model. The underlying idea of COEM is as follows. *Each time the response of a plant to a set-point signal is observed, we learn how to repeat that response, should it be required in future*.

Traditionally, adaptive control strategies have been categorized into two groups: direct and indirect. These approaches rely implicitly or explicitly on a plant model in order to derive the appropriate change in each controller parameter from the plant output error, $e_y(k)=r(k)= y(k)$. In COEM, the plant output error is not utilized and therefore no plant model is required. The lack of dependence on the plant output error, however, introduces a restriction on the application of COEM. Since the cost function is not based on the plant output error, this error is not directly minimized.

This implies that if the controller does not already stabilize the plant, COEM is not likely to cause it to do so. In other words, the controller must be able to stabilize the plant before COEM is utilized.

We consider the non linear plant

$$y(k+1) = F(y(k),...y(k-q+1),u(k),....u(k-q+1) \qquad (3)$$

where $y(k)$ is the plant output at instant k $F(.)$ is a non linear function and $u(k)$ is the control signal. The constant p and q defines the order of the plant.

At any instance the state of the plant may be defined by $S=[y(k),....y(k-p+1)]^T$ Assuming that the plant is observable). The fuzzy controller produces a control signal $u(k)$, which drives the output of the plant to $y(k+1)$. Regardless of whether or not this was the desired response, if the transition from state S to an output $y(k+1)$ is required again in future, the appropriate control signal for the plant would be $u(k)$. This is in contrast to the normal control problems where the aim is to design a controller which will drive the plant output to track the given reference signal $r(k)$.

The fuzzy controller in fig.4 outputs the signal $\hat{u}(k)$ instead of producing a control signal u(k). Thus the output error is $e_u(k)=\hat{u}(k)-u(k)$. An important point is that although $\hat{u}(k)$ is produced by the controller; it is not applied to the plant. In fact it is used to calculate $e_u(k)$. $\hat{u}(k)$ is computed by producing a new controller input vector which is passed through the fuzzy controller. A fuzzy controller can be defined as a functional relation between a set of inputs and outputs. This is given by

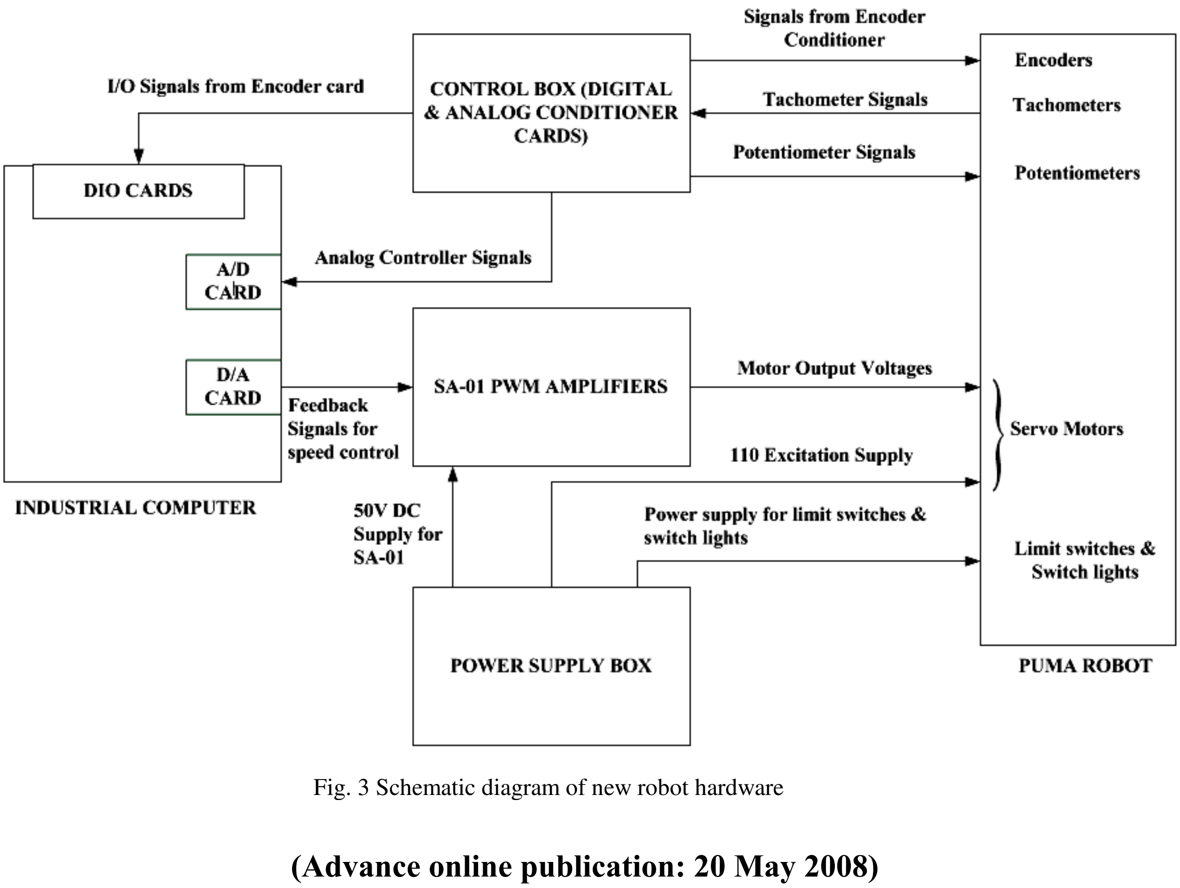

Fig. 3 Schematic diagram of new robot hardware

$u(k) = G(z(k), \Theta(k))$, where

$$z(k) = [r(k), y(k), \ldots y(k-n+1), u(k-1), \ldots u(k-m)]^T \quad (4)$$

Where G( ) is the function defining the controller characteristics, $\Theta(k)$ is the set of controller parameters and $z(k)$ is the controller input vector and, m and n are the constants. Note that $l=m+n+1$.

The fuzzy controller is parameterized by

$$\Theta(k) = \{\mu^i_j(k), \sigma^i_j(k), \beta^i(k); \mathrm{i} = 1,2....\mathrm{N};\ \mathrm{j} = 1,2,....l$$

$\hat{u}(k)$ is calculated by producing a new controller input vector, $\hat{z}(k)$ which is passed through the fuzzy controller as

$\hat{u(k)} = G(\hat{z(k)}, \Theta(k))$, where

$$\hat{z(k)} = [y(k+1), y(k), \ldots y(k-n+1), u(k-1), \ldots u(k-m)]^T \quad (5)$$

The input vector $z(k)$ differs from $\hat{z}(k)$ in the first element, where y(k+1) replaces r(k).

We have chosen to use the Gaussian membership function and the centric method of fuzzy inference in this paper as a concrete fuzzy structure to convey the idea. The method to be described in Section 4.3 is not dependent on the choice of membership function nor the choice of inference mechanism. Whether one chooses to use, for example, a triangular membership function or the Takagi-Sugeno inference mechanism, the method developed in Section 4.3 can be applied directly.

A. Fuzzy controller system

Consider the non linear plant (3). The Sugeno's type inverse fuzzy model [15] of the process can be formulated as given below:

The fuzzy rule base R contains a set of N fuzzy rules as $R = \{Rule^1, Rule^2 ......Rule^N\}$ where the ith fuzzy rule is

$$Rule^i : if\ z(k)\ is\ \tilde{A}^i\ then\ u(k)\ is\ \beta^i$$

Where

$z(k) = [z_1(k), ...z_l(k)]^T$ is a vector which contains all inputs to the fuzzy controller, and

$\tilde{A}i = [\tilde{A}^i{}_1, ...\tilde{A}_l{}^i]$ is a linguistic vector referring to fuzzy variable z (k). β^i is a consequent parameter corresponding to the control signal $u(k)$ .The number of individual membership functions for specific input value $z_j(k)$ is k_j.

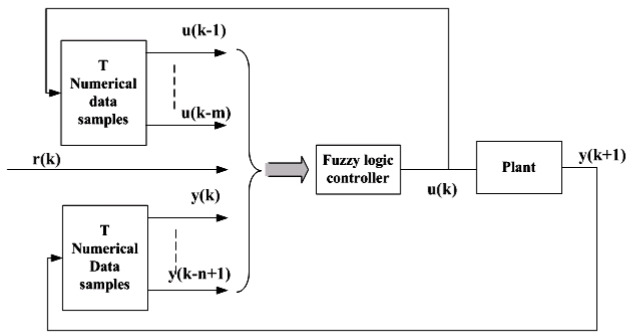

Fig.4 Fuzzy control system using COEM

In this paper the linguistic values are defined by Gaussian membership functions and are given as:

$$\tilde{A}^i_j = e^{-(z_j(k) - \mu^i_j / \sigma^i_j)^2} \quad (6)$$

Where $\sigma^i{}_j$ and $\mu^i{}_j$ are unknown constant parameters. These parameters will be adjusted on-line using a Gradient Descent Algorithm.

The output of the controller is obtained as:

$$u(k) = \frac{\sum_{i=1}^{N} \omega^i \beta^i}{\sum_{i=1}^{N} \omega^i} \quad (7)$$

Where β^i represents the consequent parameters and ω^i is the rule-firing- strength given as:

$$\omega_{\mathrm{i}} = \prod_{\mathrm{j}=1}^{1} \tilde{A}^i_j(z_j(k)) \quad \mathrm{i} = 1,2,....\mathrm{N} \quad (8)$$

B. Fuzzy control initialization

While designing a fuzzy controller, the linguistic rules are directly derived from the expert knowledge of the plant or some numerical techniques can be used to generate the rules automatically. The latter approach was utilized here.

The algorithm for initializing the controller was developed using the following steps:

1) Generate T numerical data samples (z^t, u^t) by applying random signals to the input of the plant.
2) Specify the maximum and minimum values of all inputs $\left|Z_j^+, Z_j^-\right|$ to the fuzzy controller.
3) Define a number of individual membership functions K_j for each input.
4) Determine the initial centre μ^i_j, of each antecedent membership function, distributed uniformly over the universe of Z_j using an interval $\left|Z_j^+ - Z_j^-\right| / K_j - 1$. The centers are chosen such that they are distributed evenly over the universe of Z_j.
5) Determine the dispersions, σ^i_j of the antecedent membership function as

$$\sigma^i_j = \alpha_j \left|Z_j^+ - Z_j^-\right| / K_j,\ \mathrm{i} = 1,2,....\mathrm{N} \quad (9)$$

where α_j is the interaction coefficient of membership functions.

6) From the rule-based system with all the possible combinations of the membership functions. The maximum possible number of rules is $\prod^i_{j=1} K_j$. The shape of the Gaussian membership function with 16 rules is shown in the Fig. 5.
7) A heuristic method (8) is used to set the parameters of the consequent part as

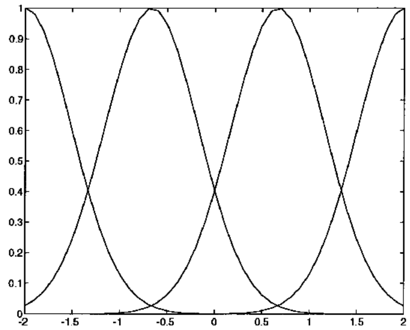

Fig. 5 Membership functions for fuzzy controller with 16 rules.

$$\beta^{i} = \frac{\sum_{t=1}^{T}\prod_{j=1}^{l}\tilde{A}_j^i(z_j^t)u^t}{\sum_{t=1}^{T}\prod_{j=1}^{l}\tilde{A}_j^i(z_j^t)} \tag{10}$$

8) If the system behavior is still not desirable, then we have to repeat the controller initialization steps with more membership functions and larger interaction coefficient.

C. Parameter adaptation using Gradient Descend Algorithm

The controller output error is used in a cost function such as

$$J(k) = \frac{1}{2}e_u(k)^2 \tag{11}$$

The adaptation of controller parameters is done to minimize the cost function. For this method to be effective, it is desirable that the membership functions employed have a continuous first derivative. The Gradient Descend algorithm is employed here.

The parameters are updated by:

$$\Theta(k+1) = \Theta(k) - \eta\frac{\partial J(k)}{\partial\Theta(k)}$$

Now using (11), the partial derivative of the cost function, *J(K)*, to each parameter can be formulated as

$$\frac{\partial J(k)}{\partial\beta^i} = -\frac{e_u(k)\omega^i}{\sum_{i=1}^{N}\omega^i}$$

$$\frac{\partial J(k)}{\partial u_j^i} = -\frac{2e_u(k)(\hat{Z}_j(k)-\mu_j^i)\sum_{l=1}^{N}\left[c_{ij}^l\omega^i(\beta^l-\hat{u}(k))\right]}{(\sigma^i{}_j)^2\sum_{i=1}^{N}\omega^i} \tag{12}$$

$$\frac{\partial J(k)}{\partial\sigma(k)} = -\frac{2e_u(k)(\hat{Z}_j(k)-\mu_j^i)\sum_{l=1}^{N}\left[c_{ij}^l\omega^i(\beta^l-\hat{u}(k))\right]}{(\sigma_j^i)^3\sum_{i=1}^{N}\omega^i}$$

Where η is the rate of descend. If the *l*th rule is dependent on the *i*th membership function of the *j*th input, $c^l{}_{ij}$ is equal to 1 otherwise equal to zero.

V. SOFTWARE DESIGN OF THE CONTROLLER

To implement the control algorithms developed in section 3, real-time software was developed using C++ and VC++ [15]. Given the nature of the hardware, the software design is based on the use of timer interrupts to generate the discrete time controller sampling period. The interrupt service routine runs the controllers for all six joints. There were some implementation constraints to optimize the code with respect to memory and computation time for real time system. To solve this problem, we have optimized our software coding to decrease the computation time, however, at the expense of memory.

At the start of operation the robot is calibrated. The calibration procedure begins by running real-time control with the encoders reset and the demand position set to 0. The real-time controller will not cause any movement as the demand position values are equal to the actual values. For each joint in turn, the main program will check the joint potentiometer value and drive the joint toward the home position. Upon reaching the potentiometer home position and locating the nearest shaft encoder index pulse the corresponding quadrature counter will be cleared and the desired value set to 0. The procedure is repeated until all joints are properly calibrated.

The graphical user interfaces developed for robot are shown partially in Fig. 6 and Fig. 7.

Fig. 6 shows different options for robot control. The "Position-Control" and "Rate-Control" are used to control the robot 6 joints' position and speed respectively. The "Signal-Generator" is designed mainly for testing the robot position-trajectory performance. The "Data-View" and "data-Curve" display the joints position and speed data. Fig. 7 demonstrates "Position-Control" window only. The software has several levels:

- System initialization and self diagnosis: which initializes custom boards, configures the robot and diagnoses each block of the system;
- System coordination and safety check: which works with the safety device to monitor robot status and stop operations in case of errors or emergency;
- Basic I/O routines for feedback information and output control signals: which reads joint encoders, position signals, estimate velocities and convert digital control signals into analog ones;
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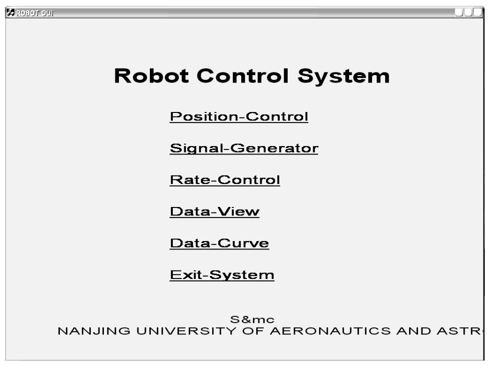


Fig.6 GUI of PC based PUMA Robot

- Kinematics & dynamic routines: This includes forward and inverse kinematics for path planning as well dynamic routines.
- User interface: This provides users with control buttons to properly operate the robot, convenient means of planning experiments and post-processing experimental data.

VI. RESULTS

For this robot, the Denavit-Hartenberg can be defined in accordance of coordinate system. Matrix A_n shows relative positioning of links.

$$A_n = \begin{bmatrix} cos\theta_n & -sin\theta_n cos\theta_n & sin\theta_n sin\alpha_n & a_n cos\theta_n \\ sin\theta_n & cos\theta_n cos\alpha_n & -cos\theta_n sin\alpha_n & a_n sin\theta_n \\ 0 & sin\alpha_n & cos\alpha_n & d_n \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{ Where}$$

$$A_1 = \begin{bmatrix} c_1 & 0 & -s_1 & 0 \\ s_1 & 0 & c_1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, A_2 = \begin{bmatrix} c_2 & -s_2 & 0 & a_2 c_2 \\ s_2 & s_2 & 0 & a_2 s_2 \\ 0 & 0 & 1 & d_2 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

$$A_3 = \begin{bmatrix} c_3 & -s_3 & 0 & a_3 c_3 \\ s_3 & c_3 & 0 & a_3 s_3 \\ 0 & 0 & 1 & -d_3 \\ 0 & 0 & 0 & 0 \end{bmatrix}, A_4 = \begin{bmatrix} c_4 & 0 & -s_4 & 0 \\ s_4 & 0 & c_4 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$A_5 = \begin{bmatrix} c_5 & -s_5 & 0 & 0 \\ s_5 & c_5 & 0 & 0 \\ 0 & 0 & 1 & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{ and } A_6 = \begin{bmatrix} c_6 & -s_6 & 0 & 0 \\ s_6 & c_6 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$c_n = \cos\theta_n$, $s_n = \sin\theta_n$ *for* $n = 1,2,.....6$ And d_n, a_n and θ_n : Constant D-H parameters.

The parameters of the robotic arm manipulators are l1=0.3m; l2=0.44m; l3=0.38m; m1=25; m2=26.3; m3=15. The friction and disturbance terms are taken as:

$$\boldsymbol{Bd} = \begin{bmatrix} 5cos(5t) \\ 5cos(5t) \end{bmatrix} \text{N-m}$$

The implementation uses 16 rules initially, with four individual membership functions for each of y(k) and r(k), i.e. *K1*=4 and *K2*=4. The interaction coefficients are $\alpha_1 = \alpha_2 = 0.7$ while $\eta = 0.01$ was used. The shape of the four Gaussian membership functions is shown in the fig

The suggested system was developed and applied to Puma 560 robot. The original proprietary controller was replaced with it. The PC runs the Windows 2000 operating system.

The PC-based controller is evaluated from two different aspects. The first aspect is to examine how easy the system integrations and modifications are. The second is to examine the performance of the control. The first aspect is obvious. The suggested PC-based hardware and software ensure that the extensibility and scalability are available. The second aspect is evaluated by the trajectory-tracking experiment.

To verify the effectiveness of the new controller, experiments were performed to test the tracking control of the robot manipulator. Firstly, each joint is separately requested to follow a desired trajectory. In this test, each joint is asked to move to a specified destination while following a predetermined path.

Fig. 8 and Fig. 9 show the desired position trajectories and position tracking errors respectively for six joints. The desired profile consists of two parts: (a) linear acceleration from rest to maximum velocity for joints 1, 2, 3 and 5 while linear deceleration for joint 4 and (b) decelerate linearly. The position tracking errors of joint 1, 3, 4, 5 and 6 are in the acceptable range of 0.005rad to 0.01rad except joint 2 for which the tracking error is 0.02rad.

To further verify the controller trajectory tracking performance, all the joints were requested to follow a varying

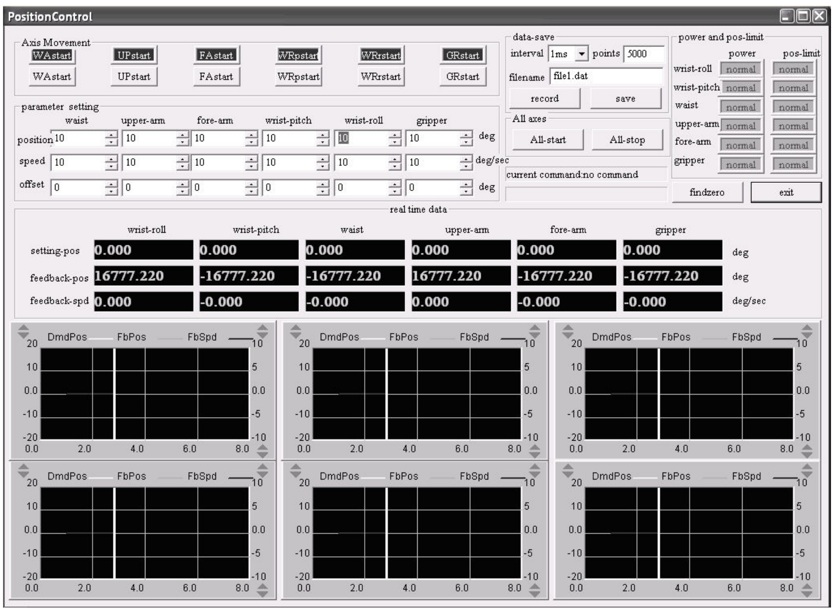


Fig.7 Robot Position-control GUI layout

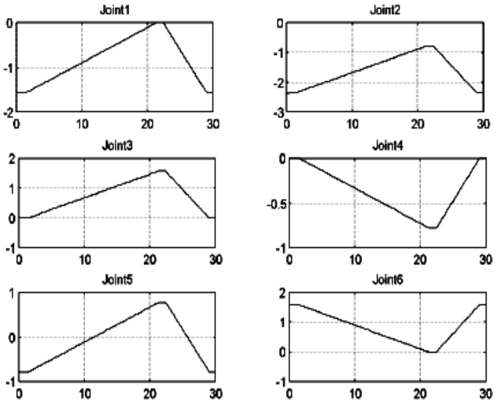


Fig 8 Desired position trajectories (Radians vs. Seconds)

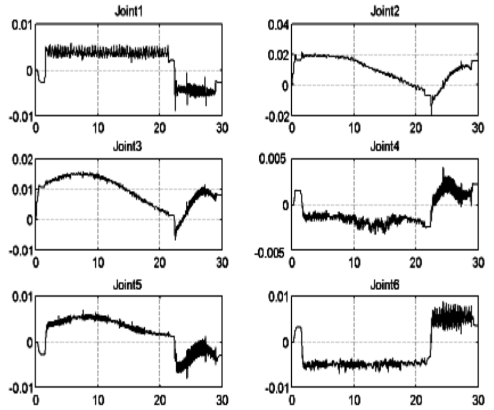


Fig 9 Position tracking error (Radians vs. Seconds)

trajectory. Fig 10 & Fig.11 shows the joint trajectory tracking performance and error respectively. All the other joints show acceptable tracking performances.

Two further tests were performed to examine the simultaneous joints movement: (1) the maximum velocity was set at 15000 counts/sec. To test the simultaneous joints movement, all six joints were asked to move at their fastest respective speeds and (2) the linear interpolation mode test in which the individual joints should arrive at their respective destinations at the same time.

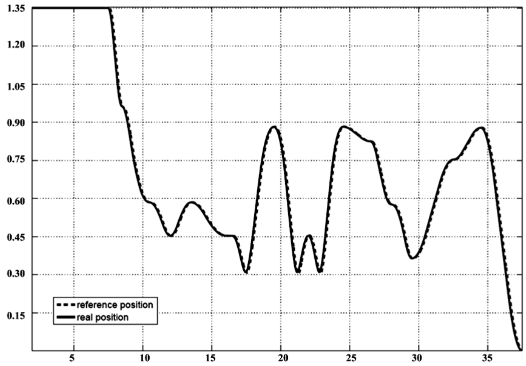


Fig.10. Comparison between planned and followed trajectory of joint1 (Radians vs. Seconds)

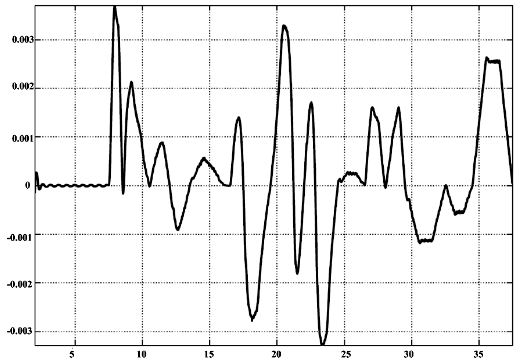


Fig.11 Trajectory tracking error for joint1. (Radians vs. Seconds)

The same tests were performed with varying joints' velocities and accelerations. Joint 1 and joint 3 showed higher position tracking errors at higher velocities and accelerations, however, all the remaining joints showed satisfactory performance. All the joints show satisfactory performance at low velocity as well as they exhibit low position tracking error while following a velocity profile at high speeds.

For robustness, The FLC is compared with the conventional PD controller. The PD controller was first well tuned for a normal operation. Then friction and disturbance was introduced in the hardware testing. The results in Fig.12 to Fig.15 show that the proposed controller for the PUMA robot is much more robust as compared to a well tuned PD controller.

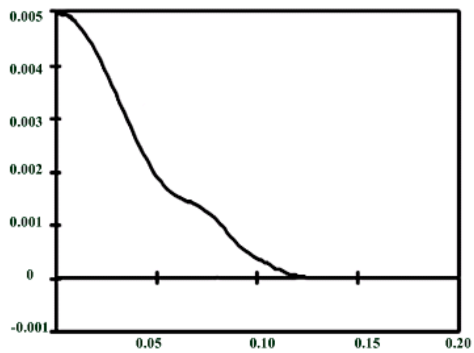


Fig. 12 FLC with friction ≈ 0.23Nm (Joint1 of robot) (Radians vs. Seconds)

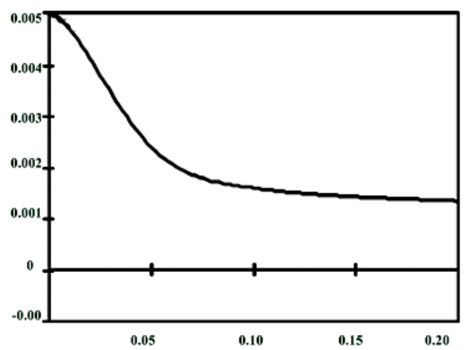


Fig. 13 PD with friction ≈ 0.23Nm (Joint 1 of robot) (Radians vs. Seconds)

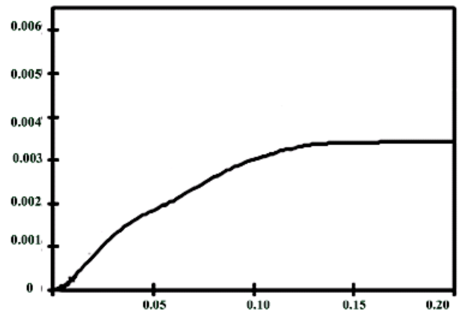


Fig. 14 FLC with unit input disturbance
(Radians vs. Seconds)

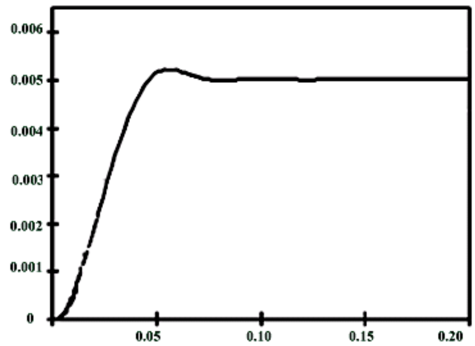


Fig. 15 PD with unit input disturbance
(Radians vs. Seconds)

Another experiment was done to compare the performance of our implemented fuzzy controller with LQR and sliding mode controller. Though the other controller also show good tracking performance, FLC was able to compensate for some disturbances and sensing noise as shown in the Fig. 16(a, b and c).

VII. DISCUSSION AND CONCLUSION

In this paper, the preliminary results are achieved in the development and implementation of a new simple PC based replacement controller for PUMA 512 robot. By assembling controller from off-the-shell hardware and software components, the benefits of reduced and improved robustness have been realized.

Although the experiments were performed at educational and research institution, the research is oriented towards industrial applications

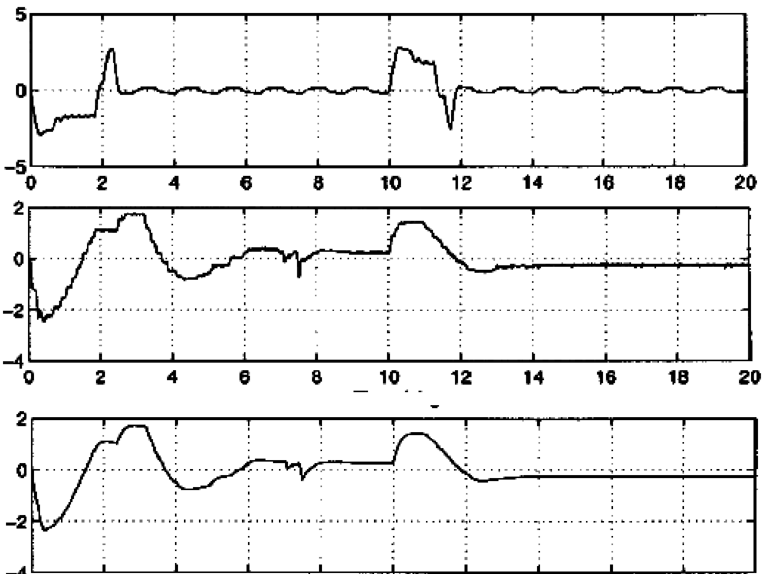
The paper uses the method “Controller Output Error method (COEM)” for on-line tuning of the fuzzy controller. This method can be used with any fuzzy controller design; the only requirement is that the controller must be stable before initializing the tuning. So any fuzzy rule-based model can be used to parameterize and initialize the controller of the system. COEM is subsequently applied to tune the parameters of fuzzy controller for purpose of achieving better performance.

Gaussian membership function and the centric method of fuzzy inference in this paper are chosen as a concrete fuzzy structure to convey the idea. The method described in Section 4.3 is not dependent on the choice of membership function nor the choice of inference mechanism. Whether one chooses to use, for example, a triangular membership function or the Takagi-Sugeno inference mechanism, the method developed in Section 4.3 can be applied directly.

Though, some technical problems were faced while performing the tests at higher velocities for joint 1 and joint 3, the newly designed hardware and software works very well and overcomes the problems in the previous PC based design for PUMA robot. All the joints show satisfactory performance at low velocity as well as they exhibit low position tracking error while following a velocity profile at high speeds.

The experimental results showed that it is feasible to implement modern control methods for PUMA 500 Series Robots through software routines running on a PC.

Presently the authors are working to implement and adapt the system for an industrial CNC milling machine.



(a)

(b)

(c)

Fig.16.Robot Joint 1 tracking performance (a) FLC implementation, (b) LQR implantation, (c) Slide mode control implementation

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