Unified Method for the Stabilization and Tracking of Single Link Robotic Arm using Adaptive FIR filter.

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This thesis, written by **Bilal shoaib** reg. number 116-FET/MSEE/F07 under the direction of his thesis Supervisor and approved by the committee, has been presented to and accepted by Committee, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN ELECTRONIC ENGINEERING.**

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Bilal Shoaib

116-FET/MSEE/F-07

بسم الله الرحمن الرحيم

In the Name of

ALLAH

Who is the Most Gracious and Merciful

قَالُوا سُبْحَانَكَ لاَ عِلْمَ لَنَا إِلاَّ مَا عَلَّمْتَنَا إِنَّكَ أَنتَ الْعَلِيمُ الْحَكِيمُ

They said: Be Glorified! we have no knowledge saving that which Thou hast taught us. Lo! Thou, only Thou, art the Knower the Wise.

[Surah Al-Baqara Verse 32]

Dedicated to my teachers and parents

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Abstract

In this work a direct adaptive FIR control is being presented. A unified design method is being proposed for stabilization and tracking of a single link robotic arm (SR-ARM). The manipulator is attached by a geared permanent magnet DC motor (GMPDC). The controller is an adaptive finite impulse response (AFIR) filter which is responsible for both stabilization and tracking. The effectiveness of the proposed scheme is demonstrated by computer simulations and real time laboratory experiments. The architecture presented is appropriate for the robust tracking of robotic system.

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Chapter 1

Introduction

1.1 Overview

Position tracking and control are always the design targets in the industrial robotic applications. This task is receiving a great deal of attentions in many engineering disciplines. Variety of elegant control strategies are developed and aimed to comprehend this promising goal. Among them a control strategy called direct adaptive control is very famous in control literature. The reason is its fine tracking and disturbance rejection capabilities. The control approach named as direct means that there is no further attempt to determine the model of the dynamics of the plant. The controller directly adjusts plant parameters with the help of measured deviation from the desired behavior. Direct adaptive control methodology provides an adapting mechanism to regulate the controller for systems having different types of structured and unstructured uncertainties to achieve desired system performance. Such uncertainties often appear in the engineering control systems [1, 2].

Direct adaptive control of linear systems has been extensively studied in literature. Systematic design procedures have been developed for model reference adaptive control (MRAC), pole placement control, self tuning regulators and multivariable adaptive control. Robustness of adaptive control with respect to the modeling errors such as external disturbance and parameter variation has been a hot research topic [6, 7, and 23]. Proportional derivative (PD) is extensively used for the stabilization of robot manipulators. Robust control algorithms are developed to adjust the gains of the system which guarantees the stability and tracking of arbitrary non linear trajectories. These controllers are designed to specify performance on given range of uncertainties. Set Point tracking using a PD or proportional integral differential (PID) compensator is attained by introducing integrator in the closed loop; this type of control is applicable to robots having very fast motion and large gear reduction [16]. By removing constant disturbance in the PD controller large gain is required keeping in view of extra burdens, integral control is used to achieve zero steady state error with small gain. [19]. Back stepping feedback linearization techniques are presented for the regulation purposes [5]. Controllers are considered for robots having two degree of freedom [6]. An efficient controller based on small gain theorem also discussed to guarantee the overall stability of the system [7].

In past years, researchers considered adaptive neural network (ANN) algorithms which are particularly useful for tracking or controlling nonlinear systems. By carefully choosing ANN structure for training weights, the researchers uses them for system modeling control applications, digital signal processing and other engineering control applications. Their ability to learn arbitrary unsmooth trajectories are efficiently utilized [3, 8, 9, and 10].

Lyapunov based direct adaptive controller combined with genetic algorithm is considered to produce both closed loop stability and desired performance of the overall system. Genetic algorithms are famous for tuning the gain of the feedback controller [21]. Direct adaptive fuzzy control for regulating higher order nonlinear continuous function based on if-then rules is presented [25].Fuzzy logic control is one of the most useful approaches for utilizing expert knowledge, having extensive research in the past years. Fuzzy logic control is generally applicable to plants that are mathematically poorly modeled. These systems are used to accomplish the predefined control and adaptive law provided that the closed loop system is globally stable provided that all the control variables are uniformly bounded and tracking error approach towards zero [14].

However the above mentioned algorithms or schemes either failed to provide the detailed analysis of the systems overall stability or they are computationally complex and expensive. Direct adaptive control (DAC) structure is composed of the plant, a stable feedback controller and an estimator. DAC scheme works on the principle that at each time instant the controller adapts the estimated plant parameter which is based on the error signal occurs from the difference between reference signal $r(t)$ and the output signal $y(t)$. The computer finds the corresponding controller parameters and then measure the contol input u which is occurs on the behalf of the output signal and controller parameters. The updating formulation of the nonlinear estimator in this type of architecture is based on the previous information obtained from the sensor (feedback). Controlling a robot manipulator in a task referenced space normally requires the conversion of the sensor outputs in the computation of the error signals and computation of joint level instructions using appropriate control scheme. These joint level commands are further computed and serves as input to the feedback loop [16].

We propose simple structure based on direct adaptive control scheme given in figure 1.1. This architecture comprises of simple adaptive finite impulse response filter to control the robot manipulator within the desired task space. The estimator (NLMS) accomplishes the task of adjusting the weights of AFIR filter (regulator) based on input and the error signal . We follow feedback architecture in which the output of the sensor is used in computation of error which is used to adjust the parameters of controller. After adjustment the learned information is used to predict the command signals required to produce desired changes towards robot manipulators. The proposed scheme is computationally simple and more accurate on tracking the desired position.

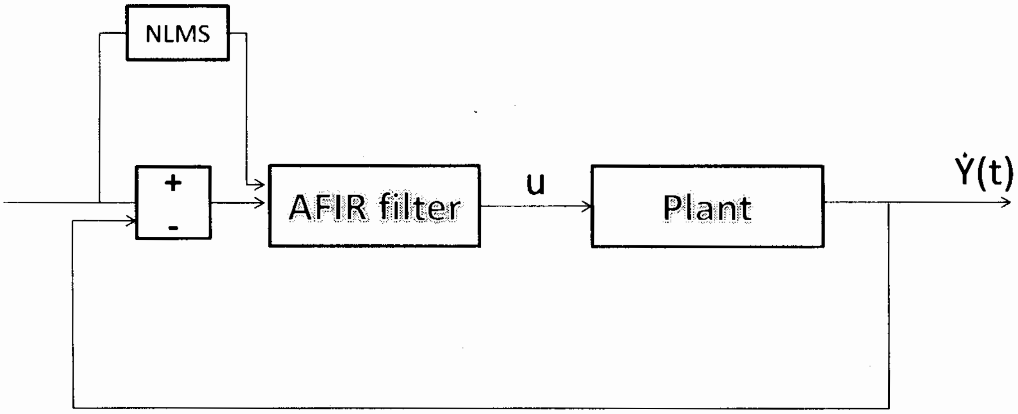


Figure 1.1 Direct Adaptive Control

The approach used in our proposed work is based on using the output error of the system to learn the normalized least mean square (NLMS) controller without the need to construct a separate plant model for the SR-ARM. Resolving the issue of stabilization and tracking. The objective of our work is to control a single link robotic arm (SR-ARM) actuated by GPMDC. The main design and implementation of a controller, which stabilizes the GPMDC motor, based SR-ARM and accomplishes arbitrary bounded trajectory in the SR-ARM task space.

Simulation results of a single link robotic manipulator driven by a GPMDC motor is documented in this report to demonstrate the effectiveness of the proposed design method's tracking performance. Performance of the system is guaranteed by suitably choosing the estimator parameters.

The overview of the adaptive filter considered in our case comprises a tapped delay line, and the error signal. The weighted signals are added and an adaptation process that automatically seeks an optimal impulse response by adjusting the weights. The input of the adaptive FIR filter is the sensor output (error) and adjustable weights computed by the estimator. The weights of the adaptive filter are adjusted by an automatic gradient based algorithm to minimize mean square error.

1.2 Problem statement

In this thesis, the equation of motion for rigid single link robot manipulator given as:

$$\ddot{q}(t) + \lambda_1 \dot{q}(t) + \lambda_2 sin(q(t)) = \tau$$

Where $\ddot{q}(t), \dot{q}(t), q(t)$ and τ describes the acceleration, velocity, position and torque applied to the robot respectively. . $\lambda_1 = \frac{\beta}{J}, \lambda_2 = \frac{Mgl}{J}$ *and* $\tau = \frac{T_m}{J}$. J denotes inertia of the arm, β defines the coefficient of friction. $M,\ g$ *and* l stand for mass, gravitational acceleration and length of the arm alternatively. It is desired to synthesis τ such that the plant output $q(t)$ tracks some arbitrary continuous trajectory $q_d(t)$, the desired output in the given space of the robot manipulator. We use an adaptive FIR filter to accomplish the objective. The weights of this adaptive filter are estimated using normalized least mean square (NLMS) algorithm.

1.3 Thesis objective

The objectives of this thesis are the following:

1. Develop a direct adaptive control (DAC) strategy based on adaptive finite impulse response filter for nonlinear dynamic SR-ARM.
2. Simulating the developed DAC strategy to test its effectiveness to control the single link robotic arm.
3. Real time implementation of the developed DAC strategy to control the position of the SR-ARM driven by a brush DC motor.
4. To achieve fine tracking using the controller based on finite impulse response filter in the DAC structure.
5. To show the closed loop stability of the rigid link manipulator model based on Lyapunov function.

1.4 Organization of the thesis

The first chapter of our thesis report revises the techniques discussed in the literature regarding position control of robot manipulators. In addition thesis objective and problem statement is also discussed here. Second chapter includes the literature review and overview of normalized least mean square algorithm. Third chapter concludes the dynamics of single link robot manipulator. Fourth chapter discusses the control law and stability issues. Fifth chapter consider simulation results. Sixth chapter covers the real time implementation and experimental results of the proposed control scheme. Seventh chapter presents the summary conclusions and recommendation for the future work.

Chapter 2

Literature review

Ossama khatib [29] in 1987 proposed a unified method for manipulator control within the task space and provide a solution of kinematics singularities. He proposed the method of controlling the motion of manipulator along a direction based on the Jacobean matrix having kinematics characteristics.

Jing Yuan [30] in 1997 expand the study of sloten in order to develop a new adaptive controller which ensures the global stability of the system via lyapunov function candidate. Main theme of his idea is to integrate both force and motion feedback signal properly. He distinguishes his idea by involving the convergence of the force error to zero. Jorge J [47] in 1999 also proposed a reduced computational method based on estimation of the manipulator dynamics with external force.

Vincente feliv, kuldip s.ratt [31] in 1990 develop an adaptive controller which estimates the gain simply by transforming the dynamic equations of the single link flexible manipulator into double integral system. By estimating the motor position in his algorithm he has an objective to remove modeling errors and nonlinearities caused by the coulomb friction.

Ydstie [33] in discussed the transient performance and limit properties of the direct adaptive control. He observed that while introducing nonzero inputs and taking leakage factor small, convergence of the adaptive algorithm is slow. He observe that the gradient based direct adaptive controller with parameter projection achieve fine gain stability.

Slotin [34] in 1992 proposed an algorithm based on direct adaptive control which compensates the plant nonlinearities using Gaussian radial basis functions. He proved the stability and convergence of his algorithm towards zero Weights are adjusted under the mechanism of lyapunov theory, which helps in achieving promising stability and performance of the dynamic plant. He derive his direct adaptive control architecture on simplified biological signal processing models and discussed them in analog, parallel computing framework. He uses Fourier analysis and Shannon sampling theorem to further approximate the nonlinear functions. Slotin [50] in 1988 discussed the comparison of PD controller and computed torque method with adaptive control scheme. In his paper he uses direct adaptive controller scheme for two degree of freedom semi direct drive robot. He shows that adaptive PD controller's works well than the other two; in terms of both accuracy and tracking. It enjoys identical level of robustness towards measurement noise.

Shuzhi s.Ge and Cong wang [28] in 2002 discusses his neural network model based on direct adaptive control architecture for the nonlinear strict feedback systems. He argues the stability of system as semi global and convergence is confirmed towards the desired trajectory, while carefully choosing the unknown parameters. The proposed architecture is a combination of DAC and back stepping which guarantees complete elimination of singularity problem. In his developed scheme the nth order subsystem is stabilized by overall closed loop system with the help of Lyapunov function V (the sum of all sub lyapunov function). Shuzhi S. Ge, T. H. Lee, and G. Zhu [24] in 1998 develop works on the principle that the desired signal is known and is stored in memory therefore making an advance decisions about the controller. The modified controller he establishes is based on least square method uses for the adaptation gain and modified error in its adaptation mechanism. He detailed that exponential stability is confirmed and rate of convergence and overshoots are calculated in terms of design parameters. K glass [30] in 1991 discusses the unconstrained motion control problem. He develops an efficient controller which does not require any knowledge about the robot dynamics and inverse dynamic calculation.

Rogelio Lozano and Bernard brogliato [36] discussed the asymptotic stability of the system. In his research work he modifies the lyapunov function to make the control input LP (linear in parameters) and also the appearance of singularity has been removed by projecting the estimates into a convex region in the parameter space. His proposed algorithm contradicts the passivity property of the joint manipulator. He ensures position and velocity tracking errors bounded towards zero.

Li Mo and M.M Bayoumi [38] in 1987 develop recursive algorithm to design a pole assignment adaptive controller. He uses recursive least square instead of simple least square to adapt the parameters of the controller explicitly. He detailed the solution of the Diophantine equation with the help of recursive least square method and the stability of the system does not effect by the existence of any temporary factor in the estimation parameter. .

Ramon R Costa [37] develop a lyapunov based direct adaptive control towards MOMO generalization for the minimum phase linear systems with relative degree one

.He propose the solution for the high frequency gain matrix through singular positive definite upper triangular matrix.

Gun Rae chi [39] in 2005 proposed a controller based on estimation using time delay and develop an internal model control strategy for the manipulators. He detailed time delay control of the robot manipulators based on IMC. He for the first time combined these two techniques. This scheme does not need the whole model of the plant and is very efficient to control the friction. The control scheme gives efficient robustness and tracking. Man Zhihong [40] in 1994 discussed the problems in robust control and deal it with variable structure compensator for the robot manipulators. His designed system ensures the elimination of the unknown effect of the external disturbances and ensures the asymptotic convergence of the error signal towards zero.

Kumpati S.Narendra and Jeyendran Balakrishnan propose a unique type of intelligent and efficient adaptive control system which is able to work efficiently in different environment. He detailed the ability of the controller to adapt any unknown but constant environment. He discusses the overall general methodology for switching and tuning between multiple models.

Wen-Jieh Wang [42] in 1989 discusses the position control of a single link flexible arm using feedback law with constant gains. The arm deflection is measured by laser beam and motor position is estimated and measured by shaft encoder. He also detailed the effect of vibration and load mass on the tracking on the arm's workspace.

Shuzhi S. Ge and C.C Hang [35] in 1997 propose an adaptive control law based on neural network to control the position and force of the robot manipulator. His contribution is eliminating the need of taking inverse of the Jacobean matrix obtain from the controller to handle the kinematics singularities. He uses Gaussian radial basis function to train the NN based controller. Jaydeep Roy and Louis L Whitcomb [45] in 2002 proposed a new position/velocity controller. He detailed two controllers one require the knowledge of the environment variables while the other adaptively determine them. He discussed the comparison of his proposed method and previously develops integral force controllers.

In case the feedback of unknown nonlinear dynamic system. It is particularly impossible to obtain the gradient of unknown function. James C, Spall and Christian [43] in 1992 proposes a new stochastic approximation algorithm for the weight estimation through the neural network technique. This controller removes the gradient approximation problem with the help of simultaneous perturbation technique. The approach used in this paper is that the output error is used to train the NN controller.

Kevin Shik Hong and Joseph Bentsman [23] in 1994 propose the model reference adaptive control for linear, multi dimensional parabolic partial differential equation. He uses the concept of persistence excitation and develops the boundary conditions for the infinite dimensional system. Adaptation laws are considered by using lyapunov redesign method. This guarantees convergence of error parameters towards zero. He also detailed the averaging theorem for finite dimensional and infinite dimensional fast system. Exponential stability of the finite dimension systems in terms of tolerance and disturbance rejection is also achieved.

Kuo-Kai Shyu, Chiu-Keng Lai, Yao-Wen Tsai, and Ding-I Yang [45] in 2002 propose a controller based on the combination of two technique linear quadratic and variable structure control to regulate the permanent magnet synchronous motor .he uses linear feedback with integral control to observe the dynamics of the feedback loop and variable structure control strategy to keep the robustness in the optimal control.

Jui-Hong Horng [47] in 1998 discusses the sliding mode control technique combined with adaptive control law for the tracking of the DC motor having unknown nonlinearities. Lyapunov approach is used to update the estimation weights of the neural controller. He argues that the proposed controller works well in any type of servo environment. He detailed the rotor follows any given desired trajectory.

Rong-Jong Wai [48] in 2004 develops an efficient controller for the nonlinear flexible arm driven by a permanent magnet DC servo motor. The motor position is measured and fed into a suitable controller for regulating the arm vibration states indirectly. The control laws are derived based on optimal control technique and lyapunov stability analysis. An adaptive controller is also established to the approximation errors introduced in the robust controller.

Ji-Liang Shi, Tian-Hua Liu [49] in 2007 proposes a unique idea of sensor less position control of permanent magnet synchronous DC motor. The detailed scheme does not require any measurement of the motor parameters, back emf and load voltage or any other operating condition of the motor or environment. The technique used here only requires slope of the current drawn by the stator. As a result this scheme is very robust and efficient for controlling the position of the PMSM. S. Kemal Ider [50] in 2002 presented a full state feedback controller to regulate the non minimum phase systems. The proposed controller is stabilized the internal dynamics of the system by placing all the poles of the system at certain distance from the imaginary axis.

Jorge J Feliu [47] in 1999 presents a new load adaptive scheme for controlling the tip position of the single link flexible robot manipulator. The only parameter required for measuring the position of the manipulator is tip load as a substitute to all the transfer functions used in other control methods. He uses CCD cameras for censoring tip position. In measuring the parameters the assumption he made is that only tip load parameter is changing in the whole system.

Jiang-Xin [51] presents the adaptive robust control for the class of uncertain nonlinear systems with parameters and system external disturbances are supposed to be unknown. These uncertainties are divided into two categories namely structured and unstructured disturbances, former will be estimated by the adaptive controller while the later is regulated by adaptive robust method. Bounded function parameters are estimated with the help of this proposed scheme.

Zhing Man, Hong Ren Wu [52] in 2006 develops a adaptive back propagation scheme for the neural network based on lyapunov stability theory. This algorithm does not search the global minimum point in the weight space along the cost function surface. The advantage here to discuss is that the constructing of energy surface is developed with a single global minimum point. The input disturbances have been eliminated with the help of lyapunov stability theory which are not considered in case of conventional neural network back propagation approach.

2.2 Normalized Least Mean Square

In discrete time domain, to execute an adaptive algorithm we assume that it receive an input pattern $\boldsymbol{r(k)}$and desired response $d(k)$ The input vector is weighted by a set of coefficients denoted by the weight vector $\boldsymbol{\theta} = [\theta_1, \theta_2, \theta_3, \dots \dots \dots \theta_n]^{\boldsymbol{T}}$. The output at time k (sampling time k=0.001T) is then obtained by an inner product of input pattern and weight vector as

$$y(k) = \boldsymbol{\theta}^{\boldsymbol{T}}\boldsymbol{r}(k) \qquad 2.1$$

The minimal disturbance architecture proposed in [15] provides an effective rule for adapting the formulation of weights. The error between the desired response and the output is as

$$e(k) = d(k) - \boldsymbol{\theta}^{\boldsymbol{T}}(k)\boldsymbol{r}(k)$$

The next error is defined as

$$e(k+1) = d(k) - \boldsymbol{\theta}^{\boldsymbol{T}}(k+1)\boldsymbol{r}(k)$$

The change in the weight vector yields a corresponding change in the error signal as.

$$\Delta e(k) = e(k+1) - e(k)$$

$$\Delta e(k) = d(k) - \boldsymbol{\theta}^{\boldsymbol{T}}(k+1)\boldsymbol{r}(k) - d(k) + \boldsymbol{\theta}^{\boldsymbol{T}}(k)\boldsymbol{r}(k)$$

$$\Delta e(k) = \boldsymbol{\theta}^{\boldsymbol{T}}(k)\boldsymbol{r}(k) - \boldsymbol{\theta}^{\boldsymbol{T}}(k+1)\boldsymbol{r}(k)$$

$$\Delta e(k) = \boldsymbol{r}(k)[\boldsymbol{\theta}^{\boldsymbol{T}}(k) - \boldsymbol{\theta}^{\boldsymbol{T}}(k+1)]$$

$$\Delta e(k) = \boldsymbol{r}^{\boldsymbol{T}}(k)[\boldsymbol{\theta}(k) - \boldsymbol{\theta}(k+1)]$$

$$\Delta e(k) = -\boldsymbol{r}^{\boldsymbol{T}}(k)[\boldsymbol{\theta}(k+1) - \boldsymbol{\theta}(k)]$$

$$\Delta e(k) = -\boldsymbol{r}^{\boldsymbol{T}}(k)\Delta\boldsymbol{\theta}(k) \qquad 2.2$$

In order to find the convergence of $e(k)$ such that it asymptotically converges towards zero is defined as

2.3

2.4

Where is chosen carefully such that the error becomes asymptotically stable and eventually approaches towards zero.

By combining the value of (2.2) and (2.4) we have

2.5

Multiplying on both sides of equation (1.4) we get

Finding the range of we use (2.3) as

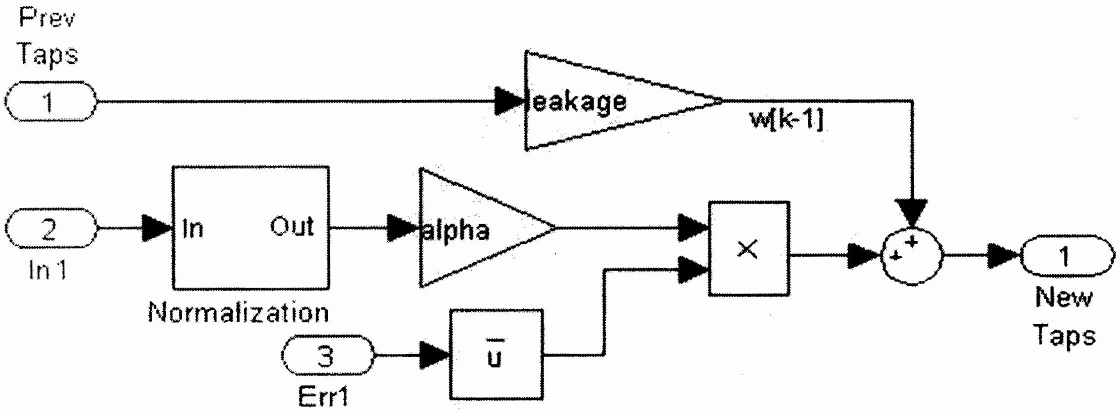
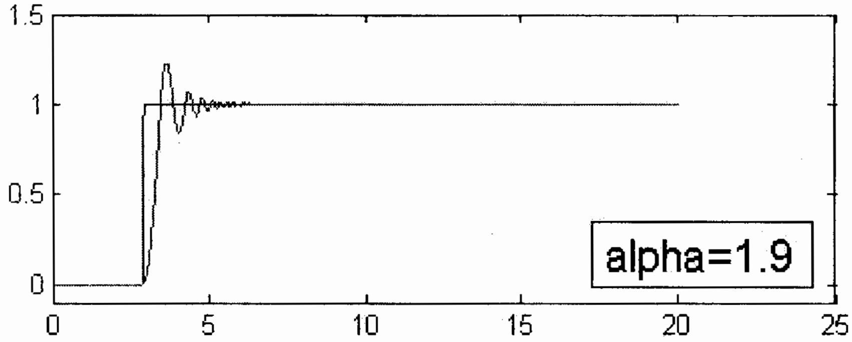
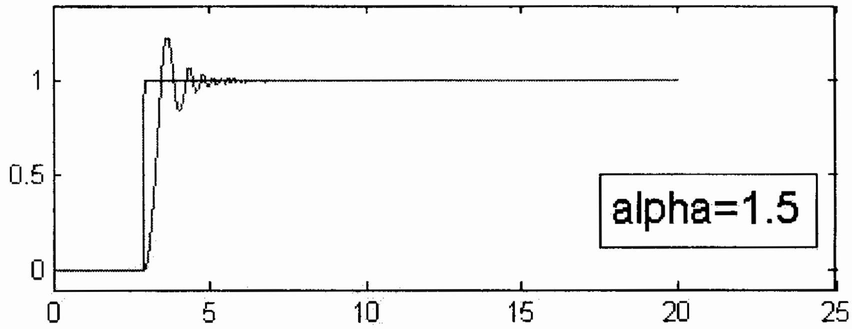
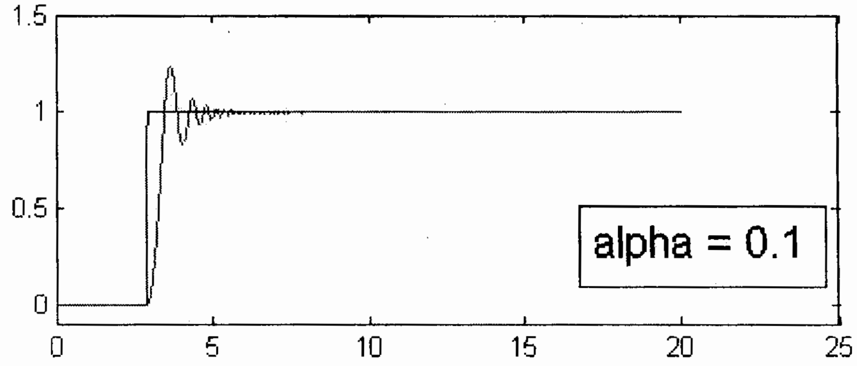


Figure 2.2 Simulink model for the nLMS

The leakage factor introduces here to implement a leaky nLMS algorithm. Including a leakage factor can improve the results of the algorithm by forcing the nLMS algorithm to continue to adapt even after it reaches a minimum value. This gain is optional and defaults to one (specifying no leakage) or set to empty. Therefore the error becomes stable if α is chosen between 0 and 2. We found that in our system is $0 < \alpha < 1.0$ is a better range. Often $\alpha \cong 0.001$ gives better results, when sampling period is 0.001 seconds. The simulink model is detailed in figure 1.2. Different values of alpha that is for example 1.9, 1.5, 0.1 and 0.01 are taken and there results are shown in the figures below.



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0
5
10
15
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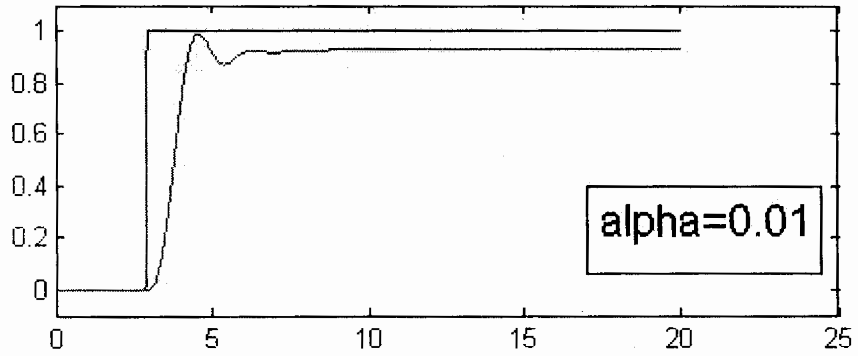
25
alpha = 0.1


1
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0.6
0.4
0.2
0
0
5
10
15
20
25
alpha=0.01

Chapter 3

Dynamics of SR-ARM

3.1 Overview

Robot Dynamic equations explicitly describe the relationship between actuation forces and motion. These equations of motion are important in considering the structure of robots, simulation and in developing the control algorithms. Dynamic equations are provided in the literature having two fundamental forms: Joint space formulation and operational space formulation. The term in joint space formulation are developed in this research work which is independent of any reference coordinate frame and have traditionally been derived using a lagrangian approach.

Lagrangian formulation fundamentally operates on the potential and kinetic energy of the robot manipulators. It also provides a detail analysis of the motion of robot manipulator and joint actuation forces.

3.2 Single Link Manipulator Model

Let us consider a single rigid link coupled through a gear train to a DC motor. Assume $q(t)$ and $q_m(t)$ denotes the angles of the link and the motor shaft respectively. Then $q_m(t) = rq(t)$ where $r:1$ is the gear ratio. The algebraic relation between link and motor shaft angle means that the system has only one degree-of-freedom and therefore we can write the equations of motion using either $q_m(t)$ or $q(t)$. In terms of $q(t)$ the kinetic energy of the system is given by

$$K = \frac{1}{2} J_m \dot{q}_m^2(t) + \frac{1}{2} J_l \dot{q}^2(t)$$

$$K = \frac{1}{2} [r^2 J_m + J_l] \dot{q}^2(t)$$

Where $J_m and\ J_l$ are the rotational inertias of the link respectively. The potential energy is given by

$$P = Mgl(1 - \cos q(t))$$

Where M denotes the mass of the link and l is the distance between joint axis and the link centre of mass. By introducing $J = r^2 J_m + J_l$. The lagrangian L of the system is given by.

$$L = \frac{1}{2} J \dot{q}^2(t) - Mgl(1 - \cos q(t))$$

Substituting this expression into euler langrange equation (2.1) yields

$$L = \frac{d}{dt} \frac{\partial L}{\partial \dot{q}(t)} - \frac{\partial L}{\partial q(t)} \qquad 3.1$$

$$J\ddot{q}(t) + Mglsin\, q(t) = \tau_l$$

Where τ_l consist of motor torque $\tau_s = r\tau_m$ which is reflected by the link and damping torques due to rotational motions $B_m \dot{q}_m(t)\ and\ B_l \dot{q}(t)$.

$$\tau_l = \tau_s - B\, \dot{q}(t)$$

Where $B = rB_m + B_l$. Therefore the final and complete expression for the dynamics of the system is given as

$$J\ddot{q}(t) + B\dot{q}(t) + Mgl\,sin\,q(t) = \tau_s$$

$$\ddot{q}(t) + \frac{B}{J}\dot{q}(t) + \frac{g}{l}\,sin\,q(t) = \frac{\tau_s}{J}$$

This may be simplified as:

$$\ddot{q}(t) + \lambda_1\dot{q}(t) + \lambda_2 \sin q(t) = \tau \qquad 3.2$$

Where

$$\lambda_1 = \frac{\beta}{J}, \lambda_2 = \frac{Mgl}{J} \text{ and } \tau = \frac{\tau_s}{J}.$$

3.3 State Space model for the SR-ARM.

In state space representation the above system of (2.2) can be written as

$$\ddot{q}(t) + \lambda_1\dot{q}(t) + \lambda_2 \sin q(t) = \tau$$

By taking $\dot{x}_1(t) = q(t) and\ \dot{x}_2(t) = \dot{q}(t)$ can be represented as

$$\dot{x}_1(t) = x_2(t) \qquad 3.3$$

$$\dot{x}_2(t) = \lambda_2 \sin x_1(t) - \lambda_1 x_2(t) + \tau \qquad 3.4$$

Matrix form of (2.3) and (2.4) is given by

$$\begin{bmatrix}\dot{x}_1(t)\\ \dot{x}_2(t)\end{bmatrix} = \begin{bmatrix}0 & x_2(t)\\ -\lambda_2 \sin x_1(t) & -\lambda_1 x_2(t)\end{bmatrix} + \begin{bmatrix}0\\1\end{bmatrix}\tau$$

$$\begin{bmatrix}q(t)\\ \dot{q}(t)\end{bmatrix} = \begin{bmatrix}0 & 1\\ -\lambda_2 & -\lambda_1\end{bmatrix}\begin{bmatrix}\sin q(t)\\ \dot{q}(t)\end{bmatrix} + \begin{bmatrix}0\\1\end{bmatrix}\tau$$

Chapter 4

Control of Single Link Robotic Arm

Control objective is to design a controller which synthesizes a control input τ. This control input compels $q(t)$ to track the desired position $q_d(t)$ in finite time.

$$lim_{t\to T}\,\tilde{q}(t) = \lim_{t\to T}\,[q_d(t) - q(t)] = 0 \qquad 4.1$$

Where, $T < \infty$ is the large time window so that the system may approach to a steady state. Further $q_d(t)$ is an arbitrary set point and $\dot{q}_d(t) = 0$.

4.1 Control Law

Control objective which we synthesize from the control input acquire the following control law.

$$\tau = -\boldsymbol{\theta}^T\tilde{\boldsymbol{q}}(\boldsymbol{t}) \qquad 4.2$$

Where $\boldsymbol{\theta}^T$ in (4.2) for our proposed controller is selected by the weight vector estimated by the gradient based adaptive algorithm. If we assume $\boldsymbol{\theta}^T$ as $\boldsymbol{k_p}$. Then this control law works as simple proportional controller but with the selection of adaptive estimation gain. (4.2) can be rewritten as.

$$\tau = -\boldsymbol{k_p}\tilde{\boldsymbol{q}}(\boldsymbol{t}) \qquad 4.3$$

4.2 Stability.

The design constraint regarding the global asymptotically stability based on the Lyapunov function presented in this section. The closed loop system is obtained by substituting the control action τ of (4.3) into the robot dynamic model (3.1) and is written as

$$\ddot{q}(t) = -\lambda_1\dot{q}(t) - \lambda_2\sin(q(t)) - \boldsymbol{k_p\tilde{q}(t)} \qquad 4.4$$

The function $\tilde{q}(t)\sin\big(q(t)\big)$ is positive definite as described in [49]. To assure the stability, Let us consider the following lyapunov function candidate

$$V\big(\tilde{q}(t),\dot{q}(t)\big) = \frac{1}{2}(\dot{q}(t) + k_p\tilde{q}(t))^2 + \lambda_2(1 - \cos\,(q(t)) \qquad 4.5$$

The first term in (4.5) is positive definite and second term which represents the potential energy is also positive definite around the equilibrium points for $q \in [-\pi,\pi]$. The time derivative of the lyapunov function candidate of (4.5) is determined as

$$\dot{V}\big(\tilde{q}(t),\dot{q}(t)\big) = \Big(\dot{q}(t) + k_p\tilde{q}(t)\Big)\frac{d}{dt}\Big(\dot{q}(t) + k_p\tilde{q}(t)\Big) + \lambda_2\tilde{q}(t)\sin(q(t))$$

$$\dot{V}\big(\tilde{q}(t),\dot{q}(t)\big) = \Big(\dot{q}(t) + k_p\tilde{q}(t)\Big)(\ddot{q}(t) - k_p\dot{q}(t) + \lambda_2\tilde{q}(t)\sin(q(t))$$

$$\dot{V}\big(\tilde{q}(t),\dot{q}(t)\big) = \dot{q}(t) + k_p\tilde{q}(t)(-\lambda_1\dot{q}(t) - \lambda_2\sin\big(q(t)\big) - k_p\tilde{q}(t) - \lambda_2\tilde{q}(t)\sin\big(q(t)\big))$$

$$\dot{V}\big(\tilde{q}(t),\dot{q}(t)\big) = -\dot{q}\lambda_1\dot{q} - \dot{q}k_p\tilde{q} - \dot{q}k_p\dot{q} - \tilde{q}\lambda_1k_p\dot{q} - \tilde{q}{k_p}^2\tilde{q} - \tilde{q}k_p\lambda_2\sin q$$

$$\dot{V}\big(\tilde{q}(t),\dot{q}(t)\big) = -(\dot{q}\lambda_1\dot{q} + \dot{q}k_p\tilde{q} + \dot{q}k_p\dot{q} + \tilde{q}\lambda_1k_p\dot{q} + \tilde{q}{k_p}^2\tilde{q} + \tilde{q}k_p\lambda_2\sin q) \qquad 4.6$$

The derivative of V along any system trajectories as shown in (4.5) guarantees asymptotically stability of the equilibrium points $[\tilde{q},\dot{q}] = 0$. The parameter vector $\boldsymbol{k_p}$ should be updated via gradient estimate.

4.3 stability analysis of gradient estimator

Let us discuss the formulation and convergence of the parameter updated so that the prediction error is reduced. This idea is implemented by updating the parameters in the converse direction of the gradient of the squared prediction error with respect to the parameters, I-e. ,

$$\dot{\hat{\boldsymbol{\theta}}} = -\rho_0 \ \frac{\partial[e^T e]}{\partial \hat{\boldsymbol{\theta}}} \tag{4.7}$$

$$\dot{\hat{\boldsymbol{\theta}}} = -\rho_0 \boldsymbol{r}^T e$$

The prediction error is related to the parameter estimation error, as can be seen from

$$e = \boldsymbol{r}\hat{\boldsymbol{\theta}} - \boldsymbol{r}\boldsymbol{\theta} = \boldsymbol{r}\tilde{\boldsymbol{\theta}}$$

$\tilde{\boldsymbol{\theta}}$ is the parameter estimation error.

$$\dot{\tilde{\theta}} = -\rho_0 \boldsymbol{r}^T \boldsymbol{r} \tilde{\theta}$$

To prove the convergence of the gradient parameter estimation we choose the following lyapunov function

$$V = \tilde{\boldsymbol{\theta}}^{\boldsymbol{T}} \tilde{\boldsymbol{\theta}} \tag{4.8}$$

Time derivative of the lyapunov function of 3.6 is

$$\dot{V} = \tilde{\boldsymbol{\theta}}^{\boldsymbol{T}} \dot{\tilde{\boldsymbol{\theta}}} + \tilde{\boldsymbol{\theta}} \dot{\tilde{\boldsymbol{\theta}}}^{\boldsymbol{T}}$$

$$\dot{V} = \tilde{\boldsymbol{\theta}}^{\boldsymbol{T}} \left(-\rho_0 \boldsymbol{r}^T \boldsymbol{r} \tilde{\boldsymbol{\theta}}\right) + \tilde{\theta} \left(-\rho_0 \boldsymbol{r}^T \boldsymbol{r} \tilde{\boldsymbol{\theta}}\right)^T$$

$$\dot{V} = \tilde{\boldsymbol{\theta}}^{\boldsymbol{T}} \left(-\rho_0 \boldsymbol{r}^T \boldsymbol{r} \tilde{\boldsymbol{\theta}}\right) + \tilde{\theta} (-\rho_0 \boldsymbol{r}^T \boldsymbol{r} \tilde{\boldsymbol{\theta}}^{\boldsymbol{T}})$$

$$\dot{V} = \tilde{\boldsymbol{\theta}}^{\boldsymbol{T}} \left(-\rho_0 \boldsymbol{r}^T \boldsymbol{r} \tilde{\boldsymbol{\theta}}\right) + \tilde{\boldsymbol{\theta}}^{\boldsymbol{T}} (-\rho_0 \boldsymbol{r}^T \boldsymbol{r} \tilde{\boldsymbol{\theta}})$$

$$\dot{V} = -2\rho_0 \tilde{\boldsymbol{\theta}}^{\boldsymbol{T}} \boldsymbol{r}^T \boldsymbol{r} \tilde{\boldsymbol{\theta}} \tag{4.9}$$

This implies that the gradient estimator is always stable and the magnitude of the parameter error is always decreasing. Therefore the stability of the k_p in (4.6) is confirmed via (4.7) to (4.9).

Chapter 5

Simulations

Let us consider a robotic arm having parameters $\lambda_1 = 5 \; and \; \lambda_2 = 2$. 10 parameter weights are selected for both the controller (AFIR filter) and estimator (NLMS). The control input saturation limits are ± 10 volts and output saturation limits are also ± 10 volts. The output saturation limits are the measures of $\pm \pi$ radians. Rate of change of actuator signal is ± 50 volts. The estimator weights are initialized by the randn MATLAB command. The values of α and leakage factor are to be taken as 0.001 and 0.99995 respectively. Parameters are updated on error based on gradient method described in section (2.6). The formulation of the weights are based on

$$\boldsymbol{\theta}(k+1) = \begin{cases} \boldsymbol{\theta}(k) & if \; e(k) = 0 \\ \boldsymbol{\theta}(k) + \frac{\alpha}{|\boldsymbol{r}(k)|^2} e(k)\boldsymbol{r}(k) & otherwise \end{cases} \qquad 5.1$$

The simulation model developed and described in (5.1). All simulations are performed in Simulink version 7.3.

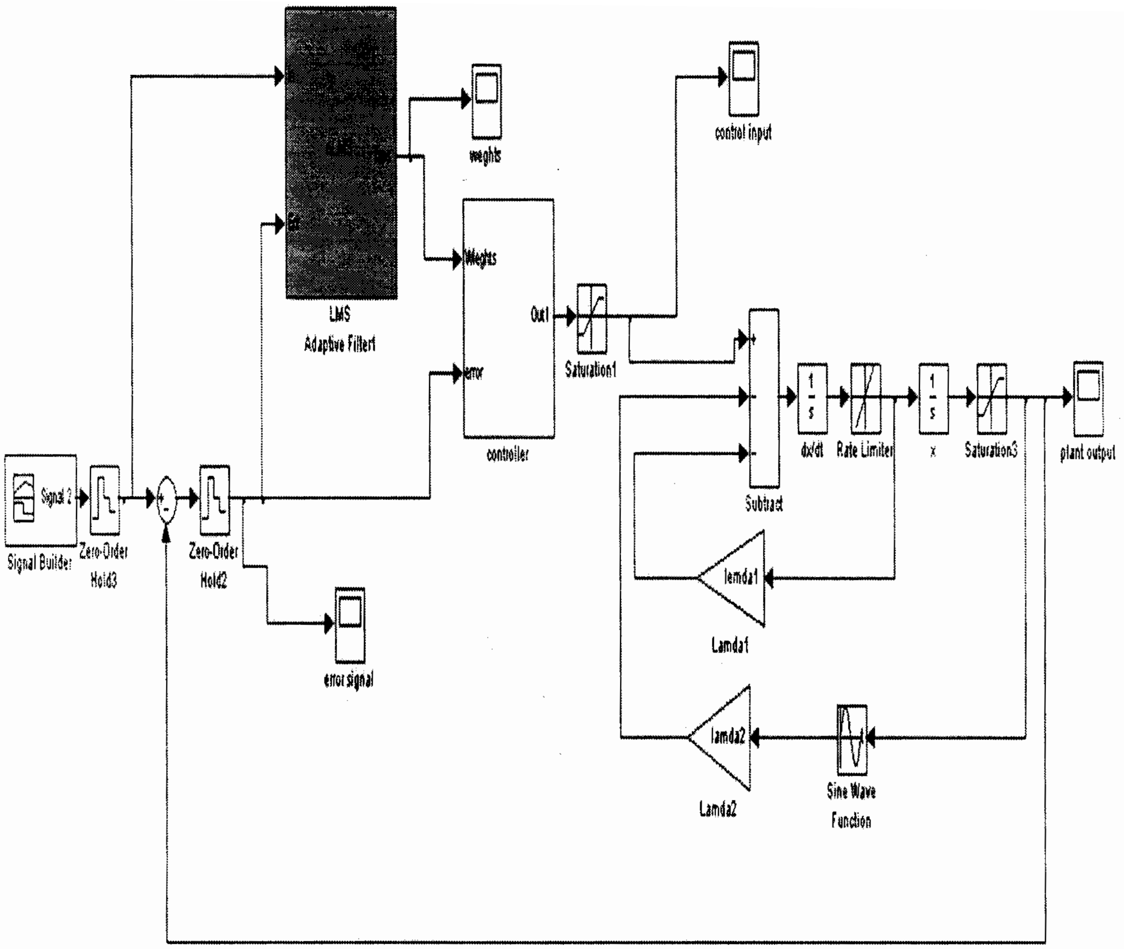

Figure 5.1 Simulation model for the SR-ARM

The figure (5.1) describes the proposed simulink model for the SR-ARM.

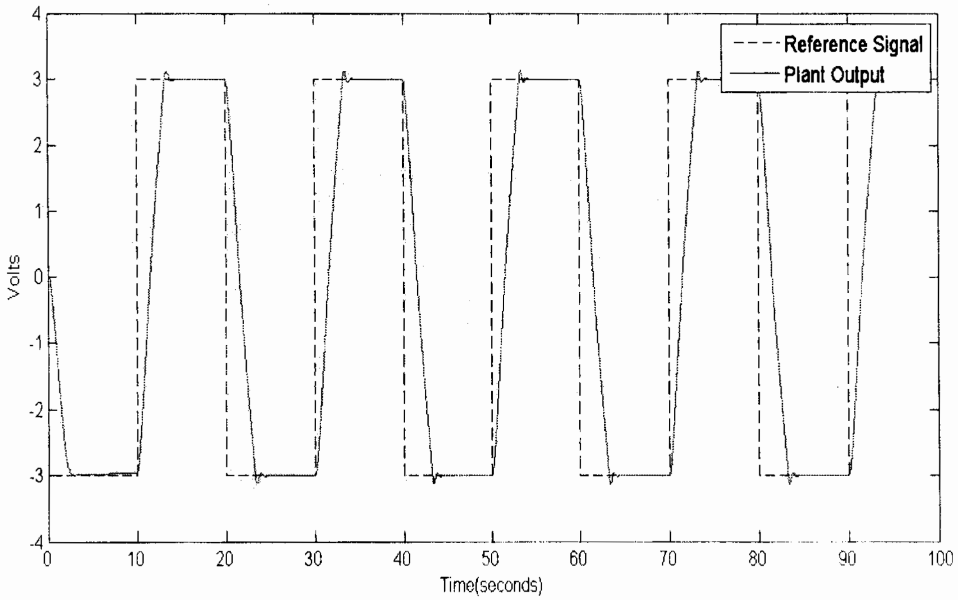

Figure 5.2 Simulation result for tracking of square wave

Figure (5.2) shows the tracking of square wave with a period of 20 sec. parameters of the estimator are selected as 10. Learning rate and leakage factor of the normalized least mean square algorithm are selected as 0.001 and 0.99995 respectively. The values of λ_1 and λ_2 are selected as described in (3.3).Figure 5.3 demonstrates the error signal. Figure 5.4 shows the control input which is bounded between ± 10 volts.

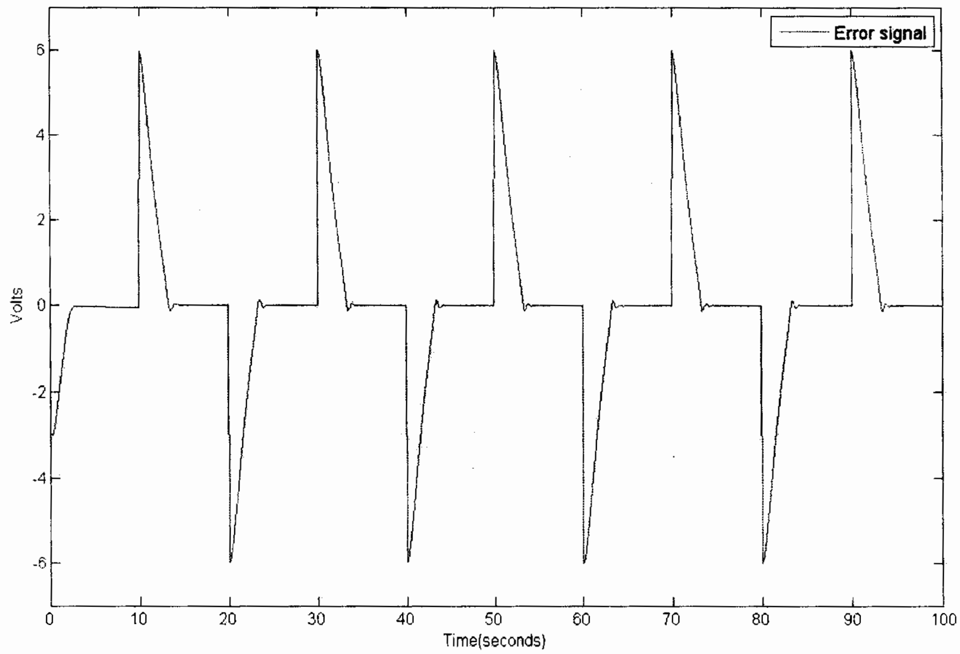

Figure 5.3 Error Signal for tracking of square wave

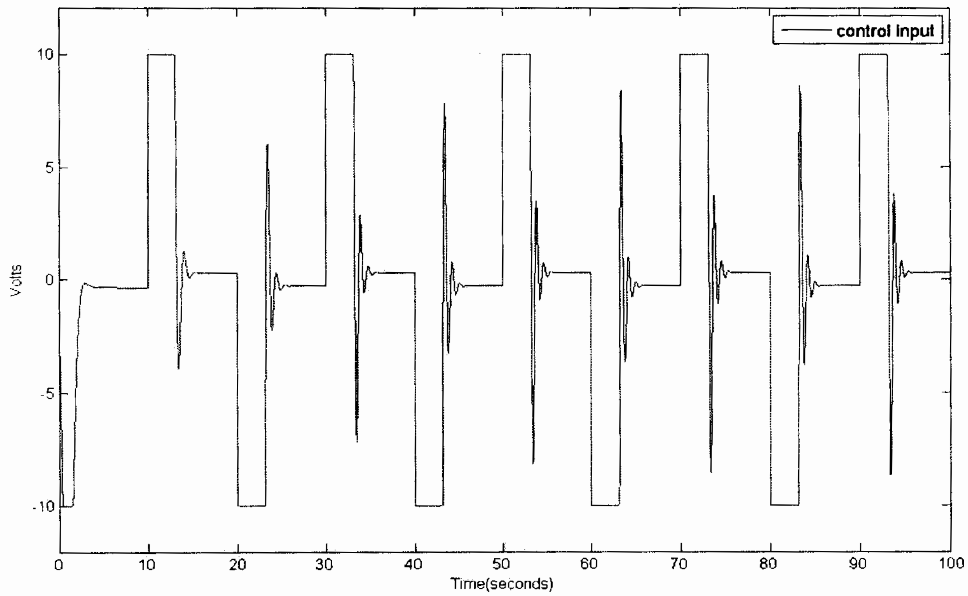

Figure 5.4 Control Input for square wave

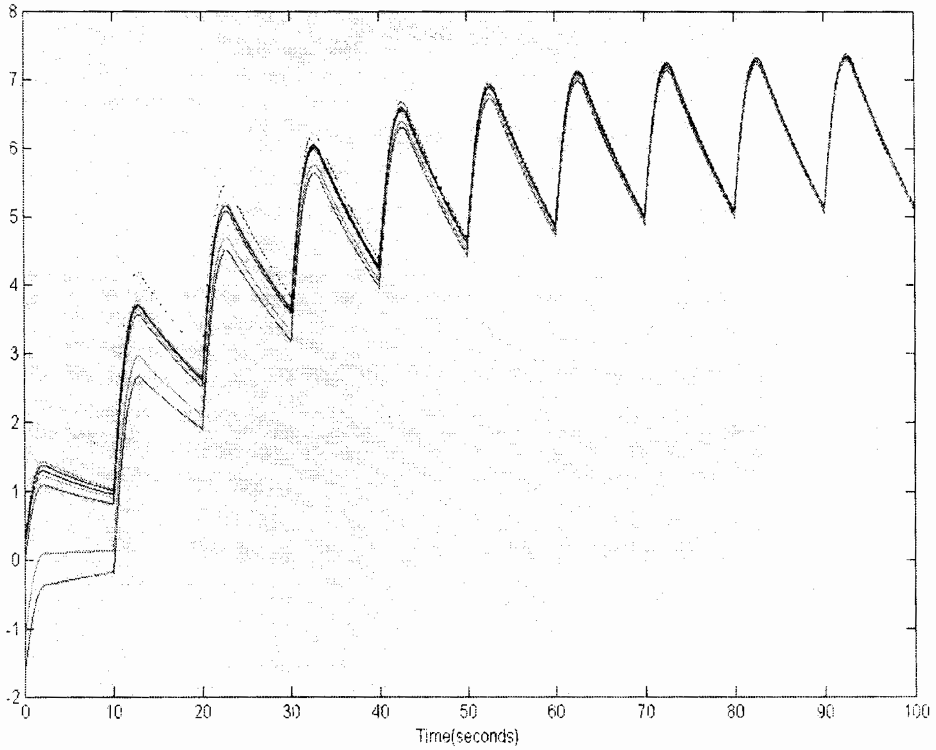

Figure 5.5 Weights of nLMS.

The above figure 5.5 shows the convergence of the weights estimated by the normalized least mean square algorithm to approximately a single value. Figure 5.6 demonstrate the tracking of sinusoidal wave. The parameters selected in the result are $\lambda_1 = 1.7$ *and* $\lambda_2 = 2.6$. Figure 5.7 indicates the corresponding the error signal.

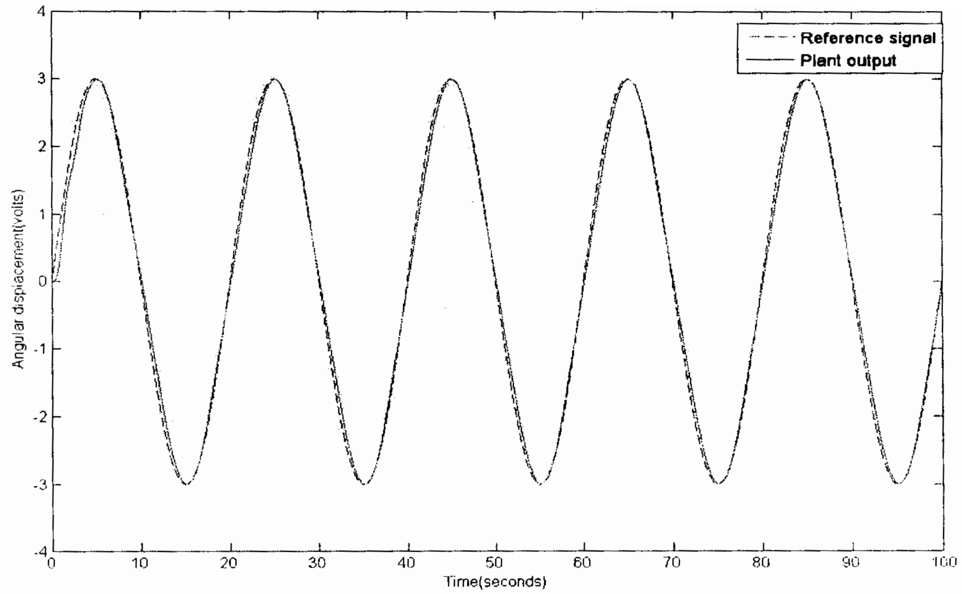

Figure 5.6 Simulation result for tracking of Sinusoidal wave.

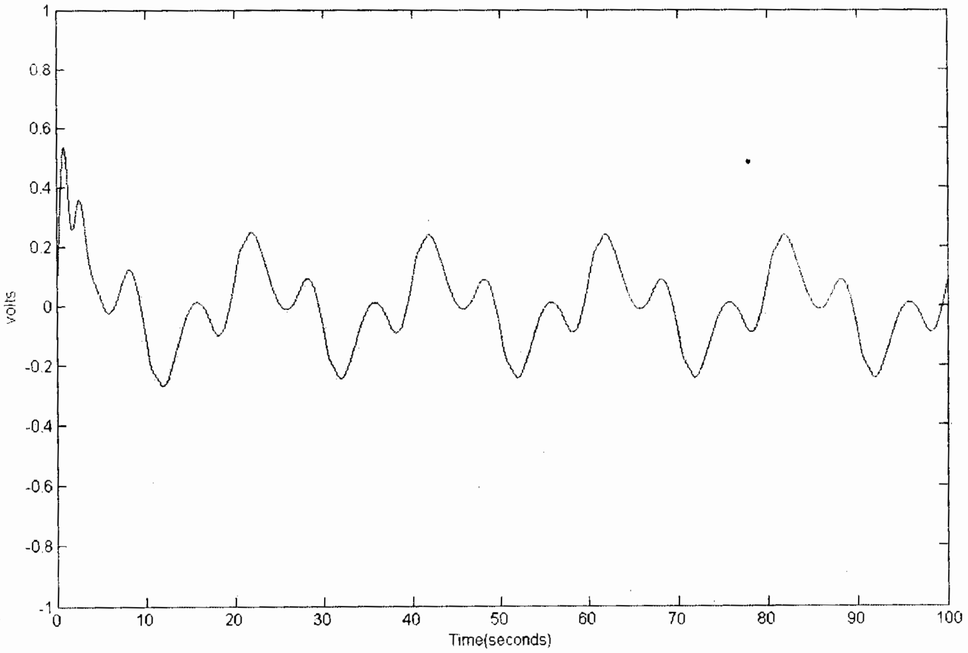

Figure 5.7 Error signal for tracking of sinusoidal wave

Chapter 6

Experimental Implementations and results

6.1 Real time experiment

A geared permanent direct current (GPMDC) motor is coupled with a 30cm rigid arm. The DC motor has a maximum speed of 3200 revolutions per minute. Potentiometer of 1 k-ohm is used for the measurement of position of the robotic arm. The resistance measurement is changed to ± 10 volts by standard signal condition method. ± 10 Volts correspond to $\pm \pi$ Radians. A house build linear servo amplifier is used to excite the GPMDC motor. Input to the servo amplifier is the output of multipurpose Advantech data acquisition card PCI-1711.

Controller computations are performed in simulink version 7.3. Data acquisition is accomplished by the software interface called real time window target. Sampling time is selected as 1msec. Standard Pentium 4(Intel coure2duo processor) is used for the computation in real time. Direct adaptive control scheme is implemented in real time environment to control the position of a single link robotic arm (SR-ARM). The experiments were carried out for the real time adaptive tracking of single link robot arm position. A block diagram explaining the setup of the SR-ARM architecture is given in figure 6.1.

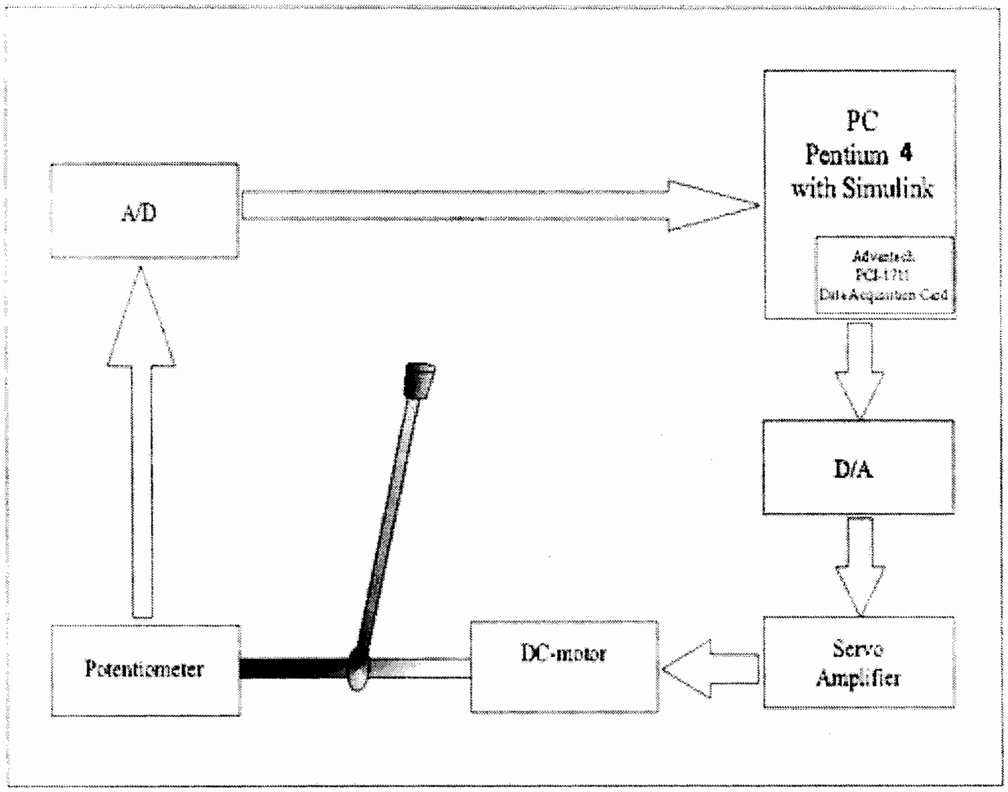

Figure 6.1 experimental setup: Block description

DC motor is coupled with an arm of length 30cm. The position of the arm is measured with a single potentiometer of one kilo-ohm. The resistance measured is changed to negative 10volts to positive 10 volts. Corresponding to the voltage from $\pm\pi$ radians.

Figure 6.2 shows the experimental setup for the single link robotic arm.

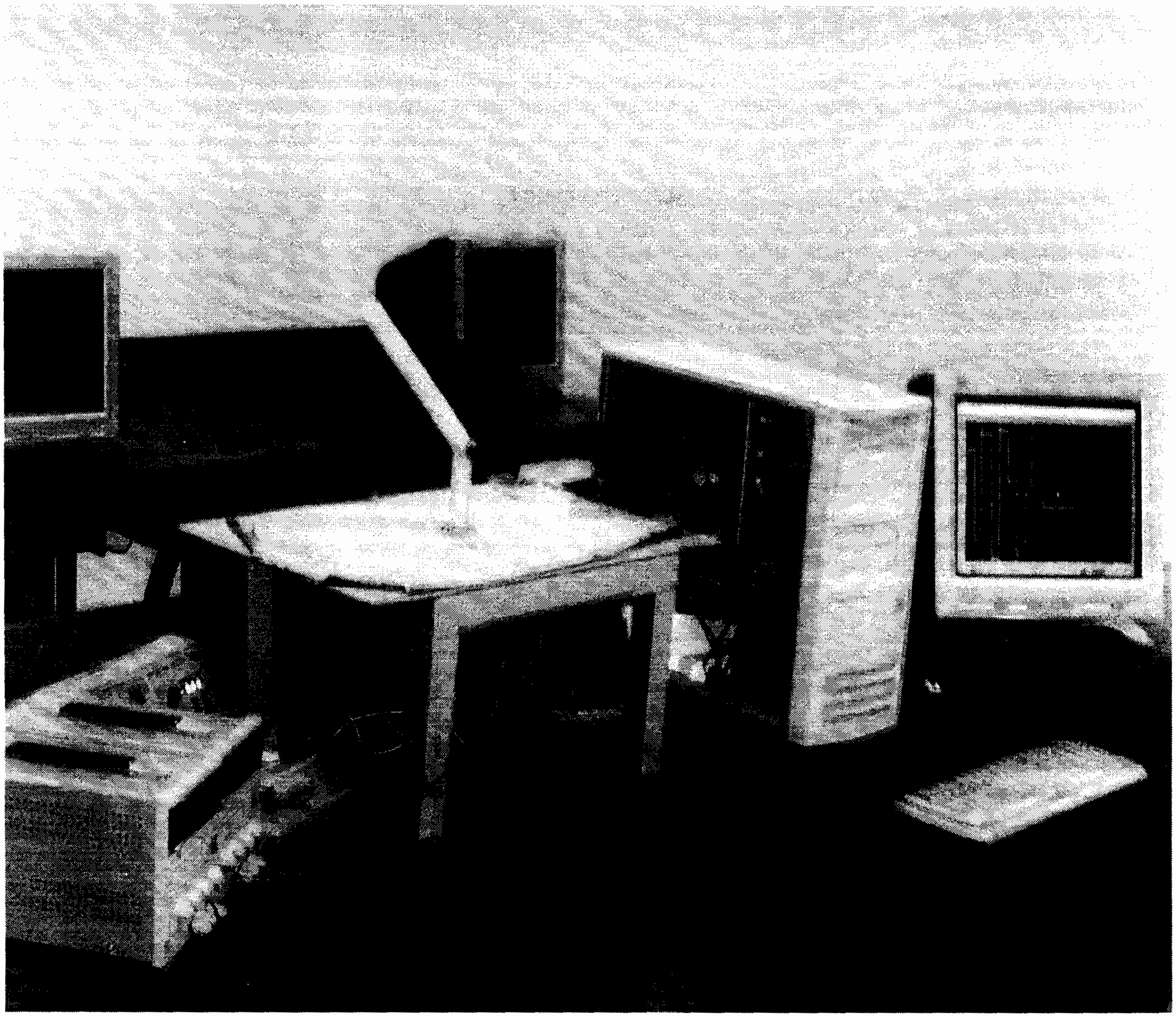

Figure 6.2 Real time experimental setup of SR-ARM

In this experiment the length of the weight vector in the Fir filter is taken to be 10, which is the order of the filter. The weights are estimated by the NLMS algorithm also having the same length of weight vector as that of FIR filter. The weights of the estimator are initialized by the randn function of MATLAB, and the leakage factor is taken to be 0.99995. All the desired output signals that are presented in the experiments are bounded in the workspace space of the robot manipulator.

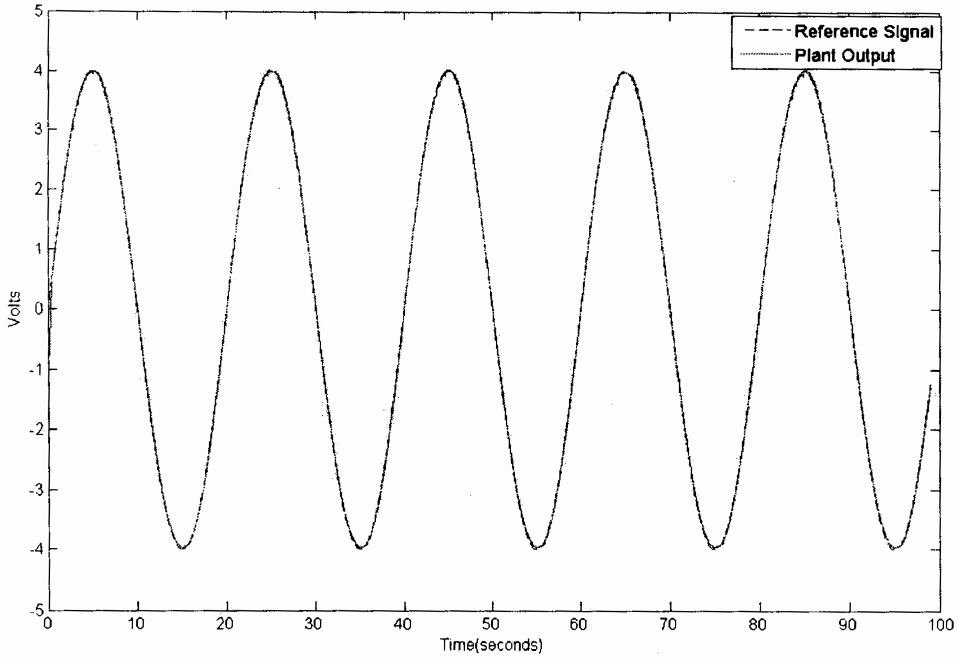

Figure 6.3 Sinusoidal Position Tracking

Desired output is sinusoidal wave having amplitude of ± 4 volts and period is 20 seconds, I.e. the signal is 4 sin (2πf) t, where f = 0.05 hertz. Figure 6.4 show the error signal which is closed to zero for the case of sinusoidal tracking. In figure 6.5 the zoomed tracking error is approximately closed to 1 percent. Figure 6.6 indicates the change in the controller output. It is observed that there are no abrupt changes in the controller output.

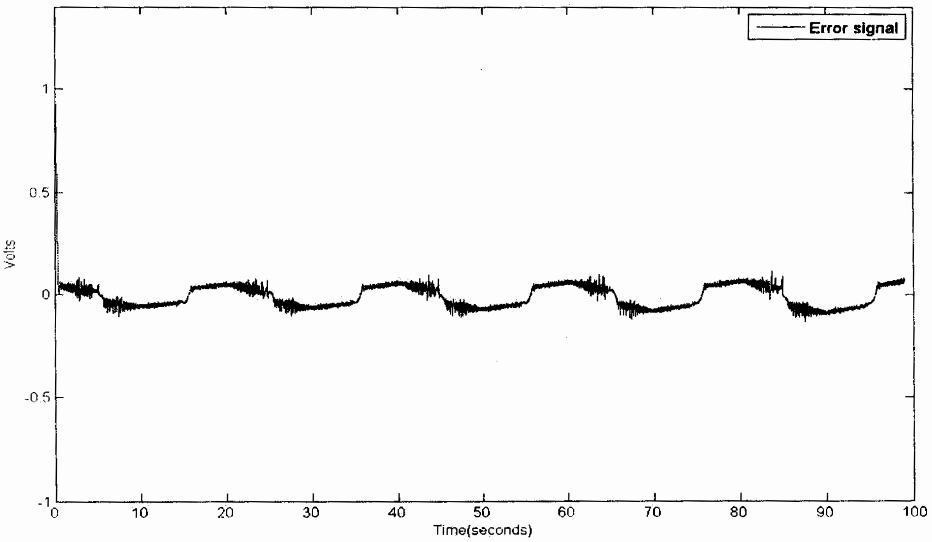

Figure 6.4 tracking error of 4 sin $(2\pi(0.05)t)$.

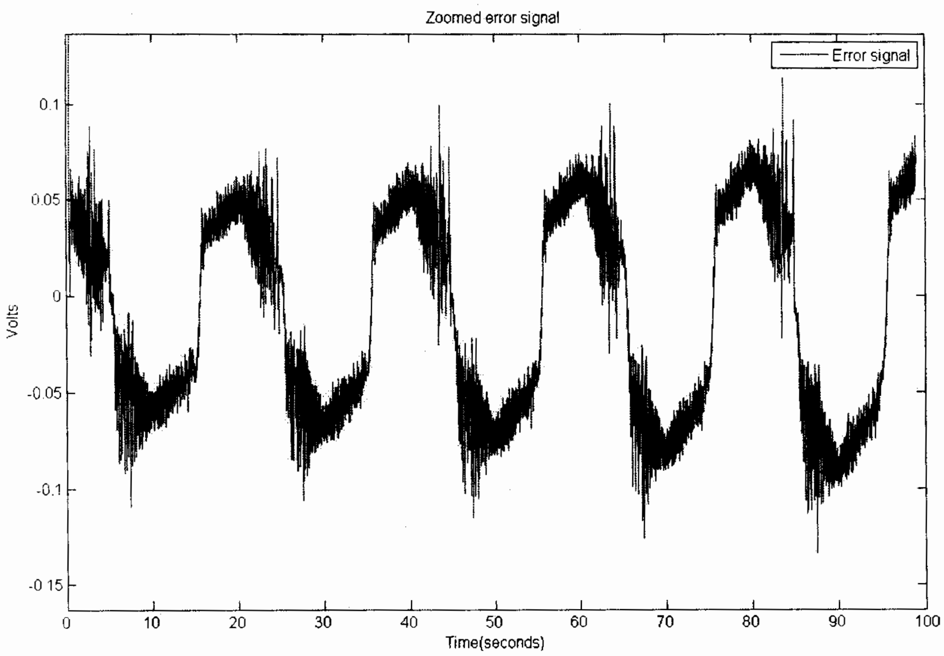

Figure 6.5 Zoomed tracking error of 4 sin (2π(0.05)t).

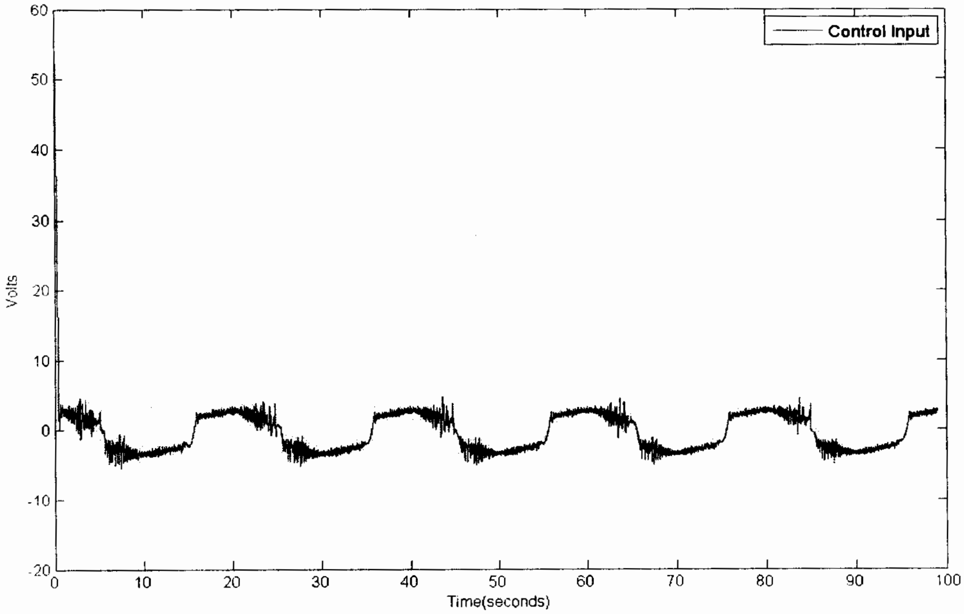

Figure 6.6 Control Input for SR-ARM.

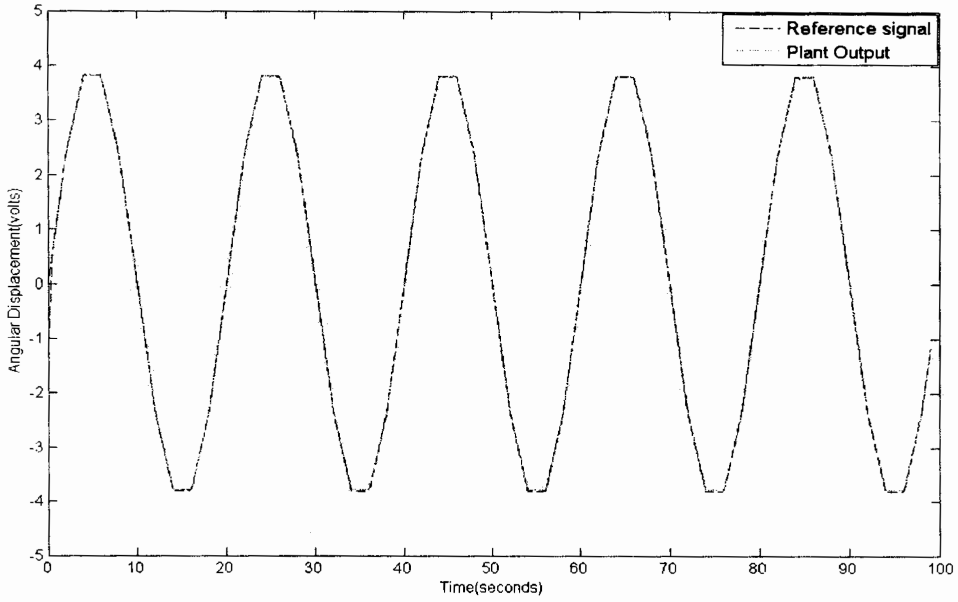

Figure 6.7 positions tracking of sample sinusoidal wave.

Desired output is the sample sine wave with sampling time of 10 seconds per sample. Weight vector for both of the controller and estimator is taken as 10. Figure 6.8 shows the error signal occurred between the desired voltage and the output voltage. A small variation around zero appears because of voltage oscillations. Figure 6.9 indicates the control input towards the robot manipulator.

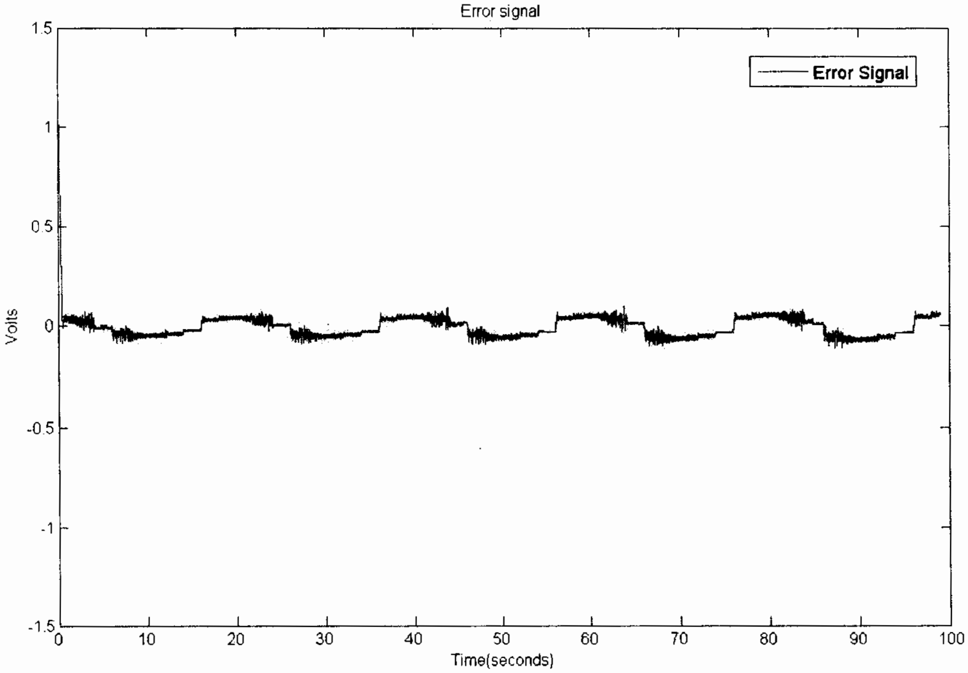

Figure 6.8 Error Signal for sample Sine wave

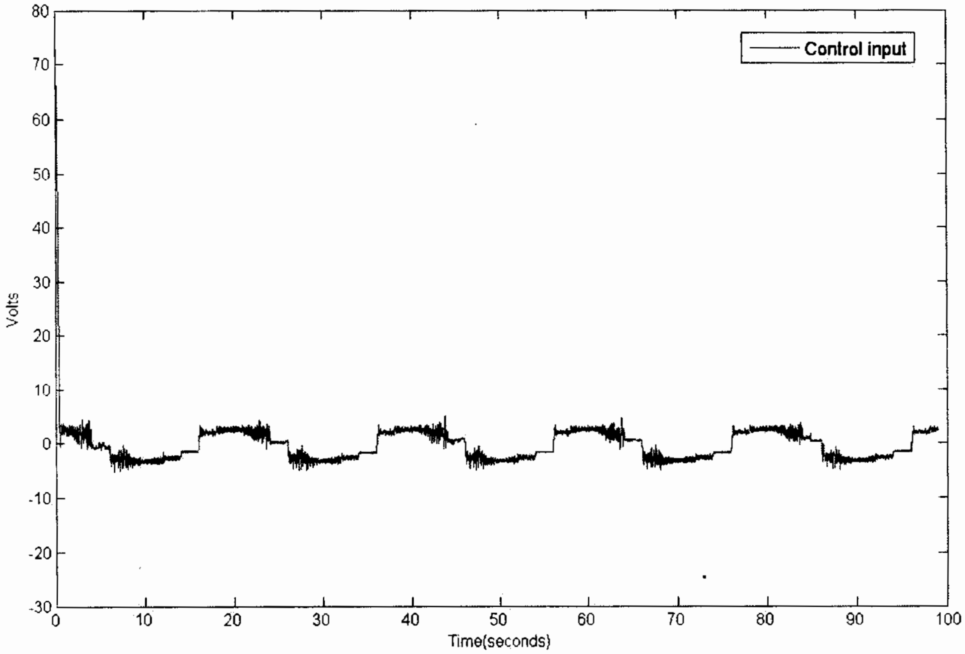

Figure 6.9 control Input

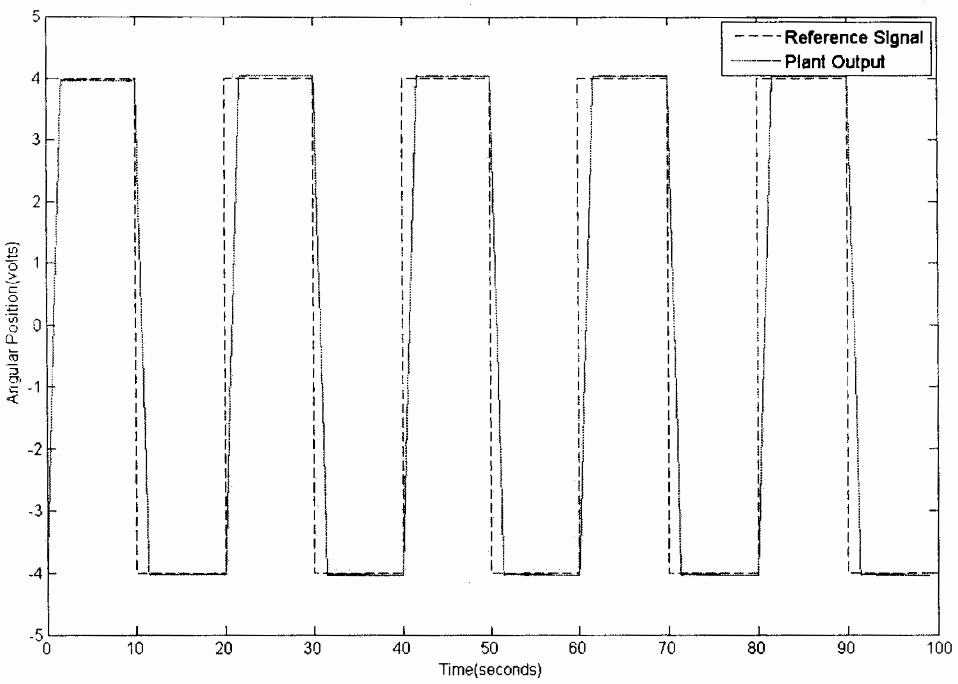

Figure 6.10 Square wave Position Tracking.

The above experiment has been performed for a square wave signal having an amplitude of ± 4 volts and a period of 20 seconds. The controller and estimator weights are the same as described above i.e. 10. It is important to point out that the measurment uncertainty of the potentiometer is ±1%. The zoomed tracking error shown in figure 6.11 which indicates that there are no oscillations in the output that there are no oscillations in the output. The experimental results depicted in figure 6.12 are corresponding to the error signal. While tracking the square wave, the notch pulses after the period of 10 seconds explains the tracking error though handling infinite frequencies.

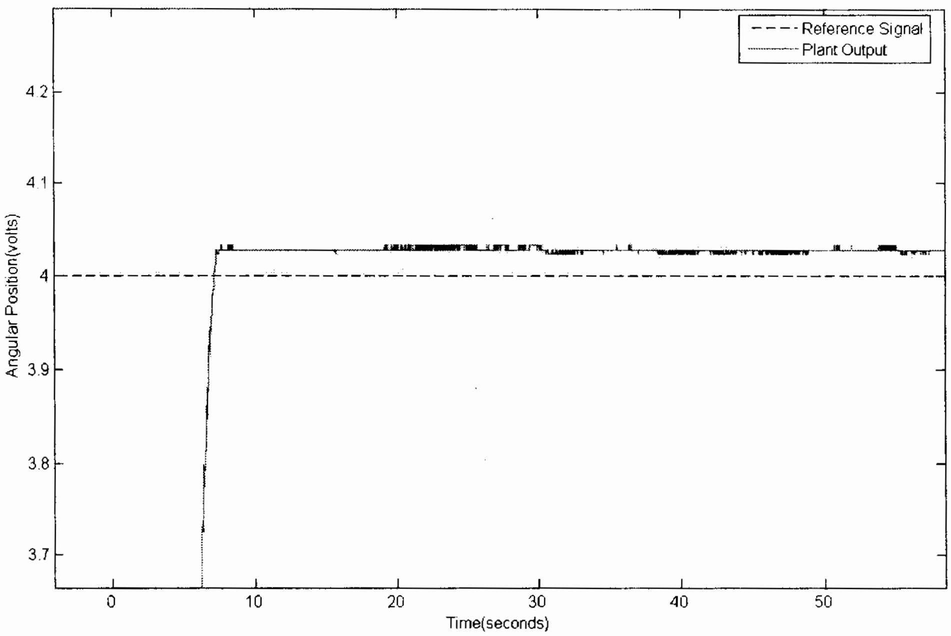

Figure 6.11 Zoomed Position tracking of square wave

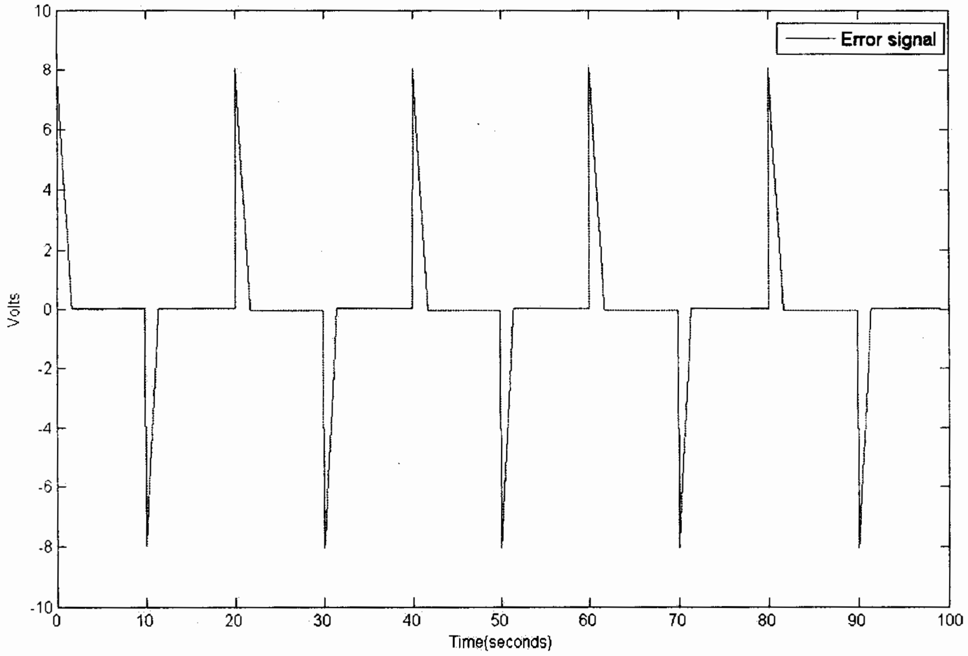

Figure 6.12 Tracking Error for Square wave

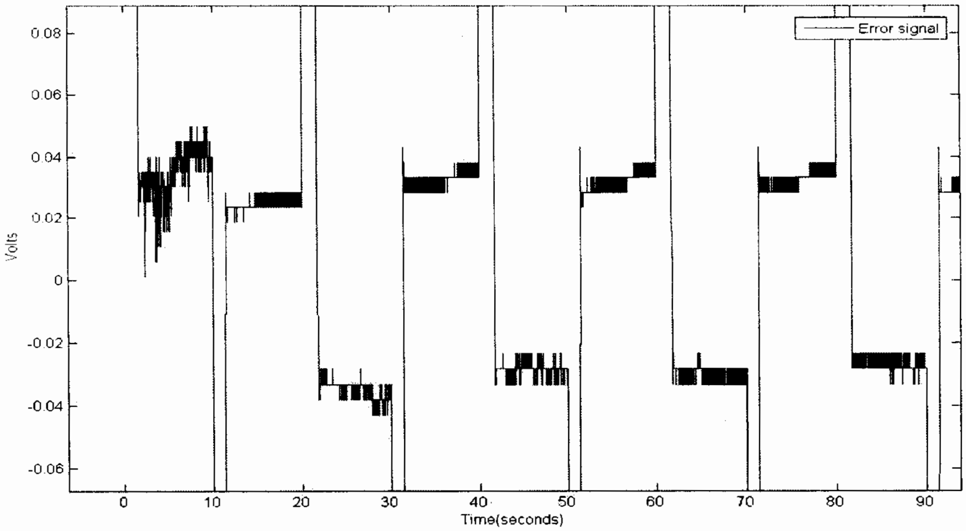

Figure 6.13 Zoomed tracking error for the square wave

The above figure 6.13 shows the steady state error which is closed to 1% and it decreases with time. Figure 6.14 provides the control signal for the controller. The control input signal to the GPMDC motor is restricted at ±10 volts. Therefore the abrupt change in the signal at the discontinuity point is not visible to servo amplifier and the GPMDC.

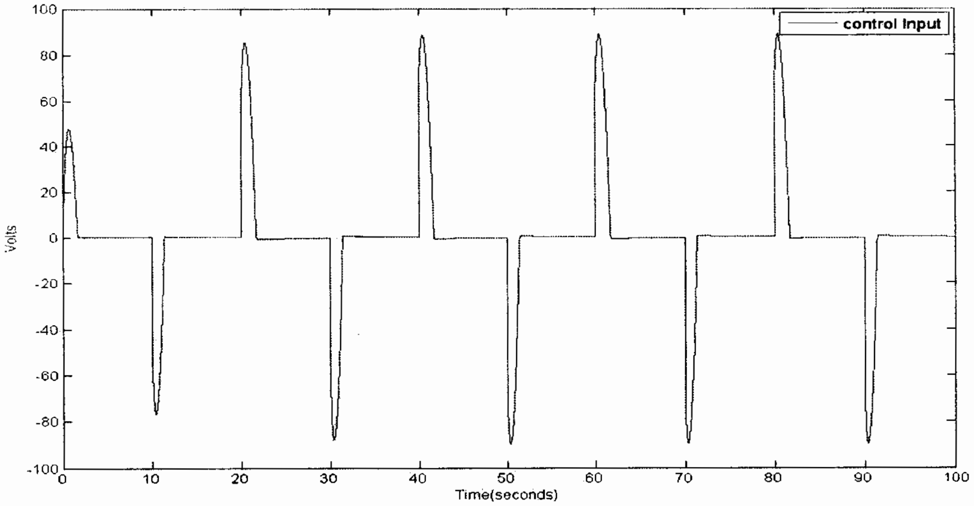

Figure 6.14 Control Input for the plant

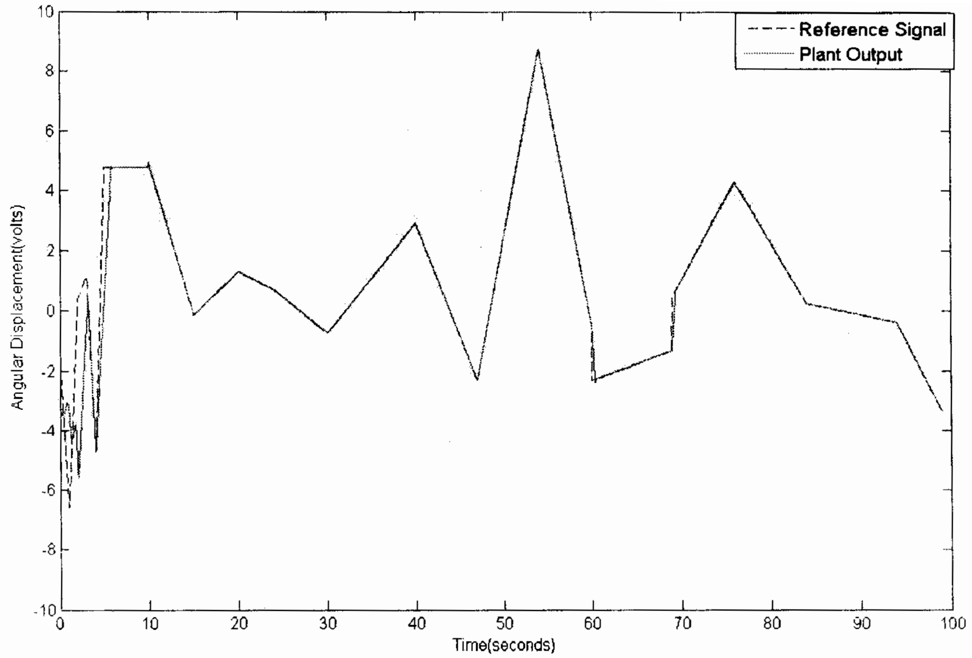

Figure 6.15 Position Tracking Time Varying signal

The above figure 6.15 shows that the proposed controller accomplishes the objective of the tracking of slowly time varying desired signals. Figure 6.16 demonstrates that the error signal exhibits the error between 0 to 10, 60 and 70 seconds which illustrates the abrupt changes in the input signal. This figure also describes that the steady state error signal is approximately between -0.1 to +0.1.

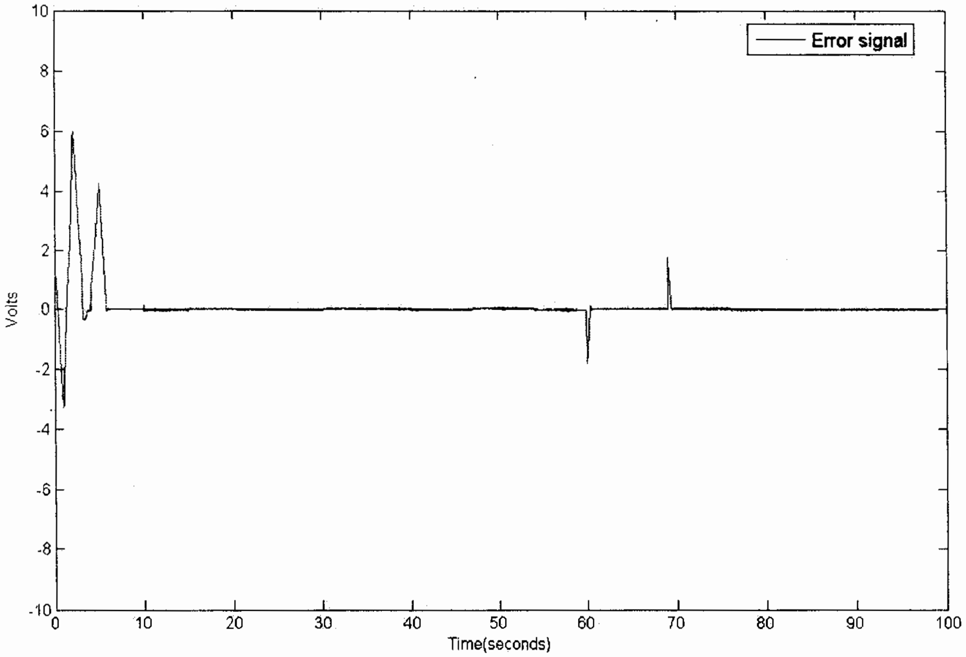

Figure 6.16 Error for time varying signal

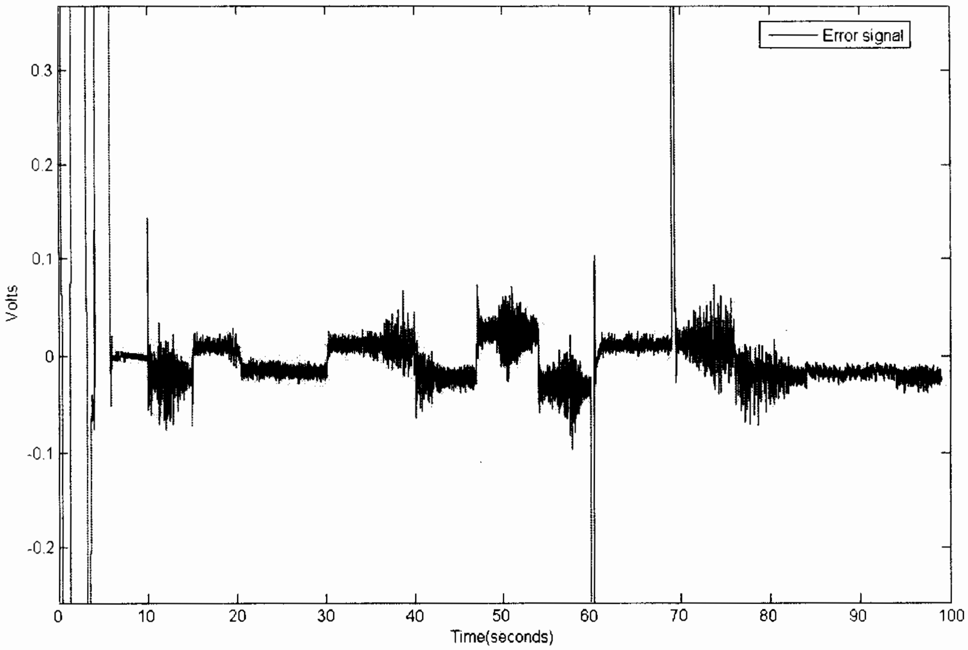

Figure 6.17 Zoomed Error for Time varying signal

Chapter 7

Conclusions and recommendations

This chapter concludes the thesis which is followed by the summary and then the recommendations for extending the work carried out in future.

7.1 Conclusions

In this thesis, a direct adaptive control (DAC) strategy is used to achieve tracking of the input reference signal for the single input single output nonlinear dynamic plant. The normalized least mean square (NLMS) algorithm is used as estimator to adjust the weights of the adaptive finite impulse response (AFIR) filter. The learning rate parameter of the NLMS is carefully selected to achieve the desired tracking performance and to increases the stability of the overall closed loop system. To test the efficiency of the developed DAC strategy has been analyzed by the simulation done for nonlinear dynamic plant.

Real time implementation of the developed DAC strategy is done for position tracking of single link manipulator driven by a permanent magnet direct current (PMDC) motor with constant loads as well as varying loads.

7.2 Summary

The contributions in this research work are as follows

- A direct adaptive control strategy is developed to control single input single output non-linear dynamic plants.

- To test the efficiency of the developed DAC strategy, simulations are carried out for single link manipulator model.
- Real time implementation of the developed DAC strategy is done to achieve position tracking of single link robot manipulator driven by a permanent magnet DC motor. The result obtained reveals the effectiveness of the proposed scheme.
- Closed loop systems stability is mathematically proved with the help of Lyapunov Direct method.

7.3 Recommendation and future work

Following are the recommendations for the possible research that can be carried out in the future based on the work presented is this thesis.

- Extension of the developed DAC strategy for multiple input multiple output nonlinear dynamic plants.
- To extend the proposed strategy for position tracking of the one link flexible manipulator.

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