

**The Control Of A Manipulator Using
Cerebellar Model Articulation Controllers**

By

Murat Darka

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Izmir, Turkey

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We approve the thesis of **Murat DARKA**

Date of Signature

.....

29.12.2003

Assist. Prof. Dr. Serhan ÖZDEMİR

Supervisor

Department of Mechanical Engineering

.....

29.12.2003

Assist. Prof. Dr. Gürsoy TURAN

Department of Civil Engineering

.....

29.12.2003

Prof. Dr. Rasim ALİZADE

Department of Mechanical Engineering

.....

29.12.2003

Assoc. Prof. Dr. Barış ÖZERDEM

Head of Department

Department of Mechanical Engineering

ABSTRACT

The emergence of the theory of artificial neural networks has made it possible to develop neural learning schemes that can be used to obtain alternative solutions to complex problems such as inverse kinematic control for robotic systems. The cerebellar model articulation controller (CMAC) is a neural network topology commonly used in the field of robotic control which was formulated in the 1970s by Albus. In this thesis, CMAC neural networks are analyzed in detail. Optimum network parameters and training techniques are discussed. The relationship between CMAC network parameters and training techniques are presented. An appropriate CMAC network is designed for the inverse kinematic control of a two-link robot manipulator.

ÖZ

Yapay sinir ađları teorisinin ortaya ıkmasıyla, robot ters kinematiđi kontrolü gibi karmaşık problemlerin özümü için alternatif methodların gelişmesi mümkün olmuştur. Serebelar Model Artikulasyon Kontrolör (CMAC) 1970 lerde Albus tarafından geliştirilen ve genelde robot kontrolü alanında kullanılan bir yapay sinir ađı çeşididir. Tezde CMAC yapay sinir ađları detaylı olarak analiz edilmiş, optimum ađ parametreleri sunulmuş ve CMAC yapay sinir ađlarına has öğretim teknikleri karşılaştırılmıştır. İki serbestlik dereceli bir robot kolunun ters kinematik kontrolü için CMAC yapay sinir ađı tasarlanmıştır ve bilgisayarda CMAC yapay ađının performansı simule edilmiştir.

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CHAPTER 1

INTRODUCTION

Due to the theoretical development and application successes, the interests in artificial neural networks have been growing in various fields of engineering. The scientists proposed many mathematical models of neural networks based on human brain and the function of biological neurons and their interconnections. The cerebellar model articulation controller (CMAC) was inspired on the knowledge of the function of the cerebellum of human brain. A theoretical model was used to explain the information processing characteristics of the cerebellum. In Great Britain David Marr in 1969 and in the US by James S. Albus in 1971 developed this model [1]. It was the model of the structure and functionality of the various cells and fibers in the cerebellum. This model makes Albus to propose a mathematical formalism for the cerebellum. CMAC is a neural network architecture. Basically, a CMAC computes the desired output by taking inputs as an address to refer to a memory where the weights are stored. CMACs estimate a relationship between the input and output by supervised training techniques.

The problem of control of a robot arm consists of arranging the motor commands at the joints so the end-effector follows a desired trajectory as precisely as possible. The efficient solution of the control problem using conventional control techniques would require a thorough knowledge of the system behavior, translated into a very accurate nonlinear mathematical model, which is typically very hard to obtain [8]. Neural network control schemes are suited to the robot control problem. In this case the approximation ability and learning capabilities make neural networks good alternatives. Instead of generating a complicated mathematical model of the robotic system, a relationship between the input and the output of the system is evaluated by the

neural networks. The CMAC neural network has the advantage of much faster convergence and online learning ability than the other networks [8].

In this thesis, CMAC neural networks are used for the inverse kinematic control of a two-link robotic arm. The control problem is analyzed in two cases. First, three desired reachable end-effector positions are specified in cartesian coordinates. A closed loop, online control is achieved by using CMAC networks. Second, the CMAC network is trained off-line. The translations of the inverse kinematics of the end-effector positions to the joint angles are evaluated with this CMAC network. The step motors are used as joint actuators. The PC interface is used for driving the step motors.

The fast convergence property, online learning and adaptive abilities are the main advantages of the cerebellar model articulation controller. Most studies in the literature are focused on the development of the training algorithm of the CMAC or the applications of the CMAC. The CMAC operation is explained in detail in this thesis. The network parameters, the training techniques and the memory requirements are expounded in detail in the following chapters.

Neural networks are used in many applications such as signal processing, image processing, speech processing, modeling, control etc... Robotic control is one of these implementations. Robotic control is based on either the task of the robotic system, the control scheme or the control subject. Neural network controllers are applied for all situations. CMAC neural networks are used as controllers for the dynamic control of robotic systems. As a matter of fact, the emergence of CMAC is based on robotic control problem. The non-linear equations of robot motion are hard to model mathematically. The actual dynamics of the robot is full of non-linearities. The conventional methods' main principle is solving a differential equation of the rotation of the joint actuators. Usually these equations consist of rotation, rotation rates, and accelerations and inertial forces. The torque is computed and it is converted to the voltage values in order to drive the individual joint actuators. This is not an exact solution because the real world variables are neglected. The CMAC learns the system dynamics with supervised training techniques and generates an input to output mapping by using simple summation operation and memory mapping algorithms.

Another robotic control problem is independent of robot dynamics. The position of the end-effector is calculated by using CMAC network in this study. The rotation rates are constant and the main reason of using neural network approach is to generate the inverse kinematics for desired end-effector coordinates.

1.1. Thesis outline

This thesis could be categorized roughly in two sections. First, it consists of information on neural networks and the CMAC neural networks. The CMAC neural networks are investigated extensively. The memory and training problems are shown, and the optimum network architecture is presented. Second the robot control problem is defined. Robotic control and the meaning of robot control are defined. The CMAC network is used for two robot learning.

Chapter two gives some background information on neural networks. This is important for two reasons: first, the basic terms and definitions of neural networks are defined, and second it is a brief summary of the CMAC networks.

Chapter three looks at the CMAC programming in MATLAB environment. The effects of the CMAC parameters and training techniques to the desired performance level are analyzed in detail.

Chapter four explains the robot control problems. It reiterates information on neural controllers. The inverse kinematics control of the two-link robot is achieved with a CMAC network. The simulation results are presented. A simple 2 DOF experimental robotic arm is presented and the position control of the arm is achieved by using CMAC network for inverse kinematics calculations.

Finally, in chapter five a discussion and suggestions for future work are presented, and the main conclusions of the thesis are summarized. The MATLAB code samples of CMAC are presented in the appendix.

CHAPTER 2

NEURAL NETWORKS

This chapter describes the artificial neural networks and CMAC. Artificial neural networks are modeled on the human brain and have a similarity to the biological brain and tries to simulate its learning process. Like the human brain, an artificial neural network also consists of neurons and connections between them. The neurons are transporting incoming information on their outgoing connections to other neurons. In artificial neural network terms these connections are called weights. Artificial neural networks are being constructed to solve problems that can't be solved using conventional algorithms. Such problems are usually optimization or classification problems like pattern classification, image processing, speech analysis, optimization problems, stock market forecasting. Artificial neural networks or shortly neural networks are in the service of engineering for control applications. Neural networks do not use the mathematical model of a system to obtain a solution but they use an input-output relationship instead and the solution is obtained by learning the relationship. Once a neural network is trained, it can determine the desired output, or solution to a given input. Neural networks can generalize some trained relationship to other untrained ones and therefore they can solve problems with limited training data. Robotic manipulator control has been one of the application areas of neural networks. With high non-linearity and modeling uncertainty, it is not easy or even possible to design a controller by conventional approaches based on the mathematical modeling. So artificial neural networks are good alternatives to conventional methods.

There are many different neural network types with each having special properties, so each problem has its own network type. Although neural networks are able to find solutions for difficult problems the results can not be perfect or exactly correct. They are just approximations of a desired solution and an error always remains. But they are good alternatives for such difficult problems.

2.1 Neural Networks

A Neural Network is an interconnected assembly of simple elements whose functionality is based on the animal neuron. The processing ability of the network is stored in weights, obtained by learning from a set of training patterns. All natural neurons have four basic components. These are dendrites, soma, axon, and synapses. Basically, a biological neuron receives inputs from other sources, combines them in an operation to output a final result. The figure 2.1 shows a simplified biological neuron and the relationship of its four components. Dendrites accept inputs, soma process the inputs and axon turns the processed inputs into outputs and synapses provide the electrochemical contact between neurons.

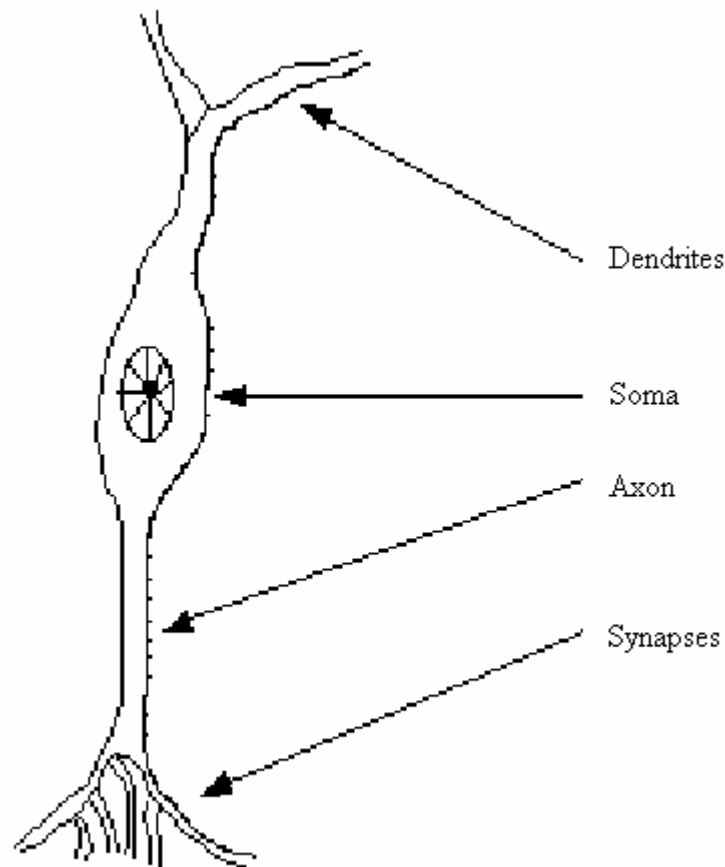


Figure 2.1 A neural cell

The Artificial Neuron is the basic unit of neural networks. They carry out the four basic functions of natural neurons. They accept inputs, and process the inputs, then

turn the processed inputs into outputs and then they contact between other neurons. Figure 2.2 shows the basics of an artificial neuron.

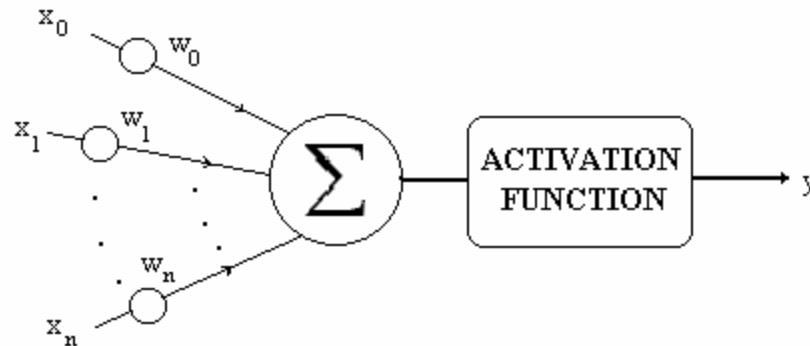


Figure 2.2 A model neuron

The inputs to the network are represented by x_n . Each of these inputs are multiplied by a connection weight, these weights are represented by w_n . Simply, these products are summed, fed through a transfer function to generate an output.

Artificial neural networks are formed by the interconnection of the artificial neurons. This occurs by creating layers that are then connected to one another. Basically, all artificial neural networks have a similar structure of topology. Some of the neurons interface the external environment to receive its inputs and other neurons provide the external environment with the network's outputs. All the rest of the neurons are in the hidden form.

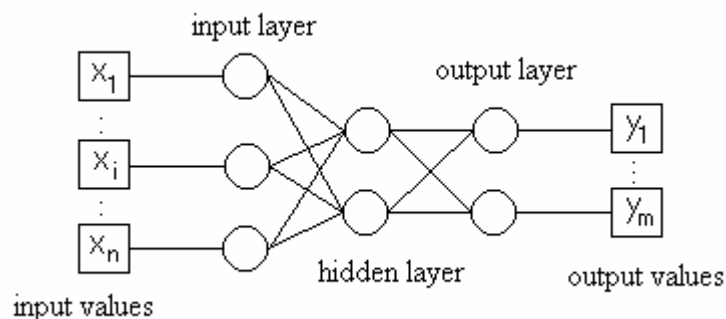


Figure 2.3 Neural network layers

Figure 2.3 shows how the neurons are grouped into layers. The input layer consists of neurons that receive input from the external environment. The output layer consists of neurons that communicate the output of the system to external environment. There are usually a number of hidden layers between these two layers; Figure 2.3 shows a simple structure with only one hidden layer. When the input layer receives the input, its neurons produce output where it becomes input to the other layers of the system. The process continues until a certain condition is satisfied.

Changing of neural networks' weights causes the network to learn the solution to a problem. The system learns new knowledge by adjusting these weights. The learning ability of a neural network is determined by its architecture and by the method chosen for training. The training method usually consists of one of two schemes:

1. Supervised Learning:

A neural network is said to learn supervised, if the desired output is already known. While learning, one of the input patterns is given to the net's input layer. This pattern is propagated through the net to the net's output layer. The output layer generates an output pattern which is then compared to the target pattern. Depending on the difference between output and target, an error value is computed. This output error indicates the network's learning effort. The greater the computed error value is, the more the weight values will be changed.

2. Unsupervised Learning:

Neural networks that learn unsupervised have no such target outputs. It can't be determined what the result of the learning process will look like. During the learning process, weight values of such a neural net are "arranged" inside a certain range, depending on given input values. The goal is to group similar units close together in certain areas of the value range.

Also, learning methods can be grouped as off-line or on-line. When the system uses input data to change its weights to learn the domain knowledge, the system could be in training mode or learning mode. When the system is being used as a decision aid to make recommendations, it is in the operation mode. In the off-line learning methods, once the system enters into the operation mode, its weights are fixed and do not change any more. In on-line or real time learning, when the system is in operating mode, it continues to learn while being used as a decision tool.

2.1.1 Learning Rules

These laws are mathematical algorithms used to update the weights.

Hebb's Rule:

If a neuron receives an input from another neuron, and if both are active (mathematically have the same sign), the weight between the neurons should be strengthened.

If "j" receives input from "k", modify the weight w_{jk} with:

$$\Delta w_{jk} = y_j \cdot y_k \quad (2.1)$$

where, y_j is the output of neuron "j" and y_k is the output of neuron "k".

Hopfield Law:

This law is similar to Hebb's Rule with the exception that it specifies the magnitude of the strengthening or weakening. If the desired output and the input are both active or both inactive, increment the connection weight by the learning rate, otherwise decrement the weight by the learning rate.

$$\Delta w_{jk} = \gamma \cdot y_j \cdot y_k \quad (2.2)$$

where γ is a positive constant representing the learning rate.

Delta Rule:

Another common rule uses not the actual activation of unit "k" but the difference between the actual and desired activation for adjusting the weights.

$$\Delta w_{jk} = \gamma \cdot y_j \cdot (d_k - y_k) \quad (2.3)$$

where d_k is the target. This is also known as the Widrow-Hoff Rule.

2.1.2 Learning Algorithms

Forwardpropagation:

Forwardpropagation is a supervised learning algorithm and describes the "flow of information" through a neural network from its input layer to its output layer.

The algorithm works as follows:

1. Set all weights to random values ranging from -1.0 to +1.0
2. Set an input pattern (binary values) to the neurons of the net's input layer
3. Activate each neuron of the following layer:
4. Multiply the weight values of the connections leading to this neuron with the output values of the preceding neurons
5. Add up these values
6. Pass the result to an activation function, which computes the output value of this neuron
7. Repeat this until the output layer is reached
8. Compare the calculated output pattern to the desired target pattern and compute an error value
9. Change all weights by adding the error value to the (old) weight values
10. Go to step 2
11. The algorithm ends, if all output patterns match their target patterns

Backpropagation:

Backpropagation is a supervised learning algorithm and is mainly used by Multi Layer-Perceptrons to change the weights connected to the net's hidden neuron layer(s).

The backpropagation algorithm uses a computed output error to change the weight values in backward direction.

To get this network error, a forwardpropagation phase must have been done before. While propagating in forward direction, the neurons are being activated using the sigmoid activation function.

The formulation of sigmoid activation is:

$$f(x) = \frac{1}{1 + e^{-input}}$$

(2.4)

The algorithm works as follows:

1. Perform the forward propagation phase for an input pattern and calculate the output error
2. Change all weight values of each weight matrix using the formula

$$\text{weight}(\text{new}) = \text{weight}(\text{old}) + \text{learning rate} * \text{output error} * \text{output}(\text{neurons } i) * \text{output}(\text{neurons } i+1) * (1 - \text{output}(\text{neurons } i+1))$$

4. Go to step 1
5. The algorithm ends, if all output patterns match their target patterns

2.1.3 Types of Neural Networks

There are several types of neural networks exist. They can be distinguished by their type or their structure and the learning algorithm they use. Feedforward neural networks allow only neuron connections between two different layers, while feedback networks have also connections between neurons of the same layer.

1) Perceptron (Single Layer Networks):

It is a very simple neural network type with two neuron layers that accepts only binary input and output values (0 or 1). The learning process is supervised and the network is able to solve basic logical operations like “AND” or “OR”. It is also used for pattern classification purposes. More complicated logical operations (like the XOR problem) can not be solved by a Perceptron.

2) Multi Layer Feedforward Networks:

It is an extended Perceptron and has one or more hidden neuron layers between its input and output layers. It is mainly used in complex logical operations and pattern classification.

3) Recursive Networks:

They consist of a set of neurons, where each neuron is connected to every other neuron. There is no differentiation between input and output neurons. The main application is the storage and recognition of patterns.

2.2 Cerebellar Model Articulation Controller

The CMAC neural network, based on the cerebellar neuromuscular control, is basically a nonlinear lookup table technique which maps n-dimensional input to a corresponding output. The CMAC was first proposed by Albus [1], [2], [3] and has been modified and improved. These studies focused on development of algorithms [9], [11], [13], improvements of CMAC structure, and applications [8], [10], [12], [15].

Lin and Chiang described the CMAC technique with mathematical formulation and use the formulation to study the CMAC convergence properties. Both information retrieval and learning rules are described by algebraic equations in matrix form. Convergence characteristics and learning behaviors for the CMAC with and without hashing are investigated with the use of these equations [7]. Thompson and Kwon studied the sequential neighborhood training and random training techniques for CMACs. These techniques were used to generate mathematical functions. In the neighborhood sequential training method, a strategy was devised for selecting points in the input space which would train CMAC systems in the most rapid manner. The random training method was found to converge on the training function with the greatest precision, although it requires longer training periods than the neighborhood sequential training method [6]. Commuri and Lewis developed novel weight update laws that guarantee the stability of the closed loop system. The passivity properties of the CMAC under the specified tuning laws are examined and the relationship between passivity and closed-loop stability is derived [13]. Çetinkunt, Abdelhameed and Pinspon showed that the CMAC based controller causes instability after a long period of real time runs. They proposed a new learning algorithm. They used their controller for the trajectory tracking control of a piezoelectric actuated tool post. The performance of the proposed controller is compared with conventional controllers. The experimental results showed that the performance of the CMAC based controller using proposed learning algorithm is stable and more effective than that of the conventional controllers [10].

The CMAC is the simple model of the cerebellum. It is a mathematical formalism developed by Albus to model the information processing characteristics of the cerebellum. The brief structure of the cerebellum is first outlined. Then the CMAC network is described.

2.2.1 The Cerebellum

This section explains how the information process is achieved in the cerebellum of humans and other mammals. The cerebellum is attached to the midbrain and nestles under the visual cortex as shown in Figure 2.4. It is involved with control of movements of the body. Injury to the cerebellum results in movement disability such as overshoot in reaching for objects and lack of coordination. During 1960s, the functional interconnections between the principal components of in the cerebellar cortex are identified. A brief outline of the structure and the function of the cerebellar cortex is shown in Figure 2.5.

The principal input to the cerebellar cortex arrives by mossy fibers. Mossy fibers carry information from different sources such as the vestibular system (balance), the reticular information (alerting), the cerebral cortex (sensory motor activity), and sensor organs that measure such quantities as position of joints, tension in tendons, velocity of contraction of muscles, and pressure on skin. Mossy fibers can be categorized into two classes based on their point of origin: those carrying information that may include commands from higher levels in the motor system, and those carrying feedback information about the results of motor outputs. Each of mossy fibers makes excitatory (+) contact with granule cells [1].

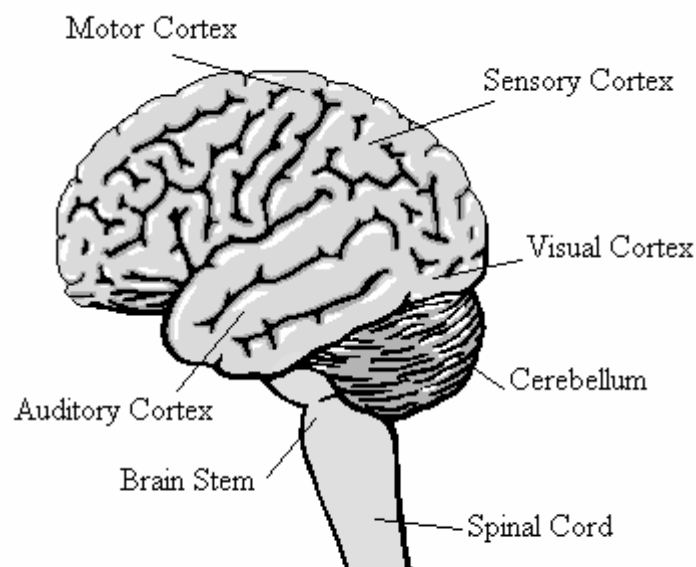


Figure 2.4 Exterior view of human brain [21]

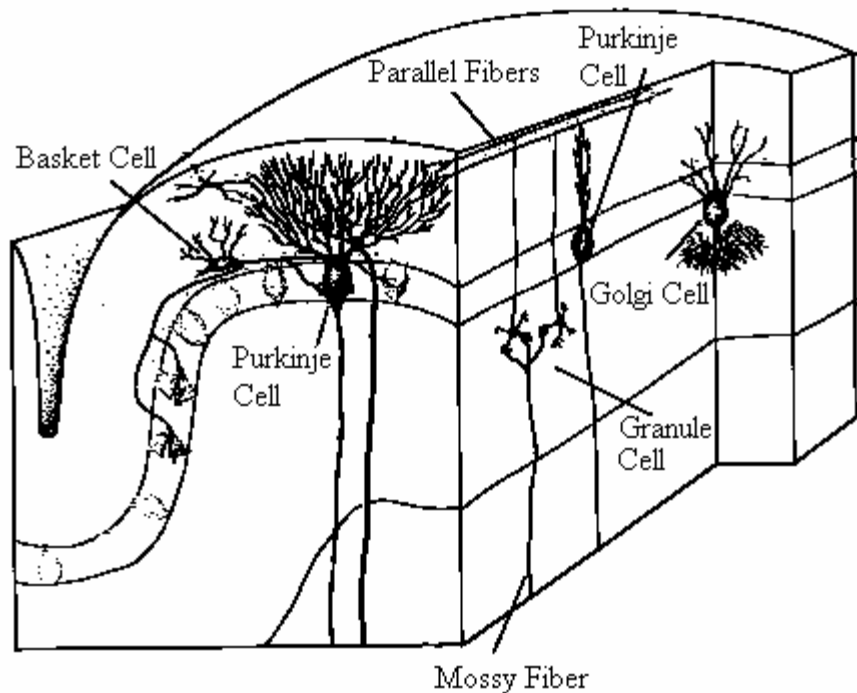


Figure 2.5 Neuron cells in cerebral cortex

Golgi cells sample the response of the granule cells by the parallel fibers and suppress by inhibitory (-) contacts all but the most highly excited granule cells. Purkinje cells are the output of the cerebellar cortex. They sum the excitatory (+) effect of parallel fibers through weighted connections. They also receive inhibitory (-) input from parallel fibers by basket cell inverters. The strengths of these weights determine the transfer function of the cerebellar cortex. Climbing fibers are believed to adjust the strength of these weights so as to train the cerebellum [1].

2.2.2 The CMAC Network

The detailed knowledge of the structure and the function of the various cell and fiber types in cerebellum make it possible to form mathematical models to explain the information processing characteristics of the cerebellum. The general outlines of CMAC model are shown in Figure 2.6. Albus has produced the version illustrated in Figure 2.7 [1].

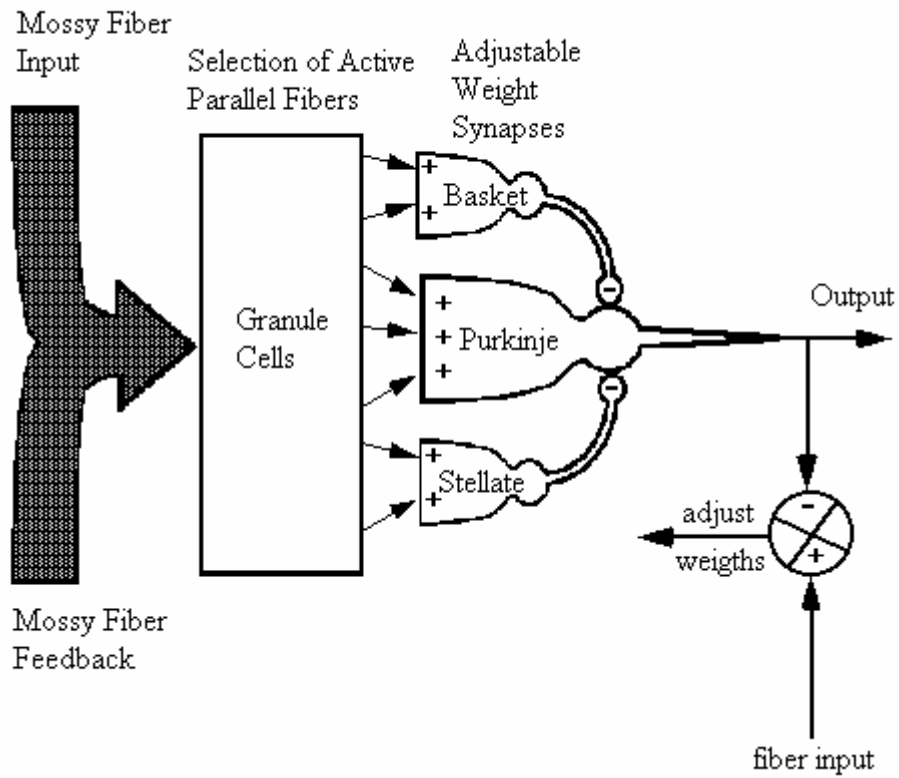


Figure 2.6 A Theoretical model of the cerebellum [1]

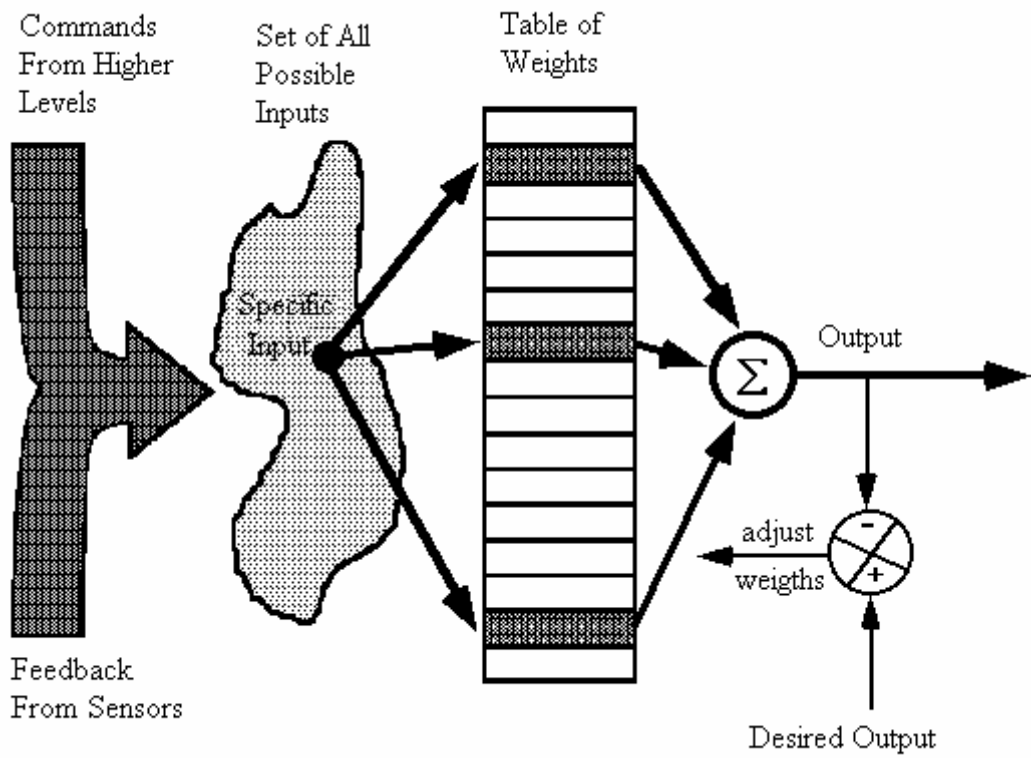


Figure 2.7 A schematic representation of CMAC [1]

The CMAC, as a controller, computes control values by referring to a memory look-up table where those control values are stored [2]. Memory table basically stores the relationship between input and output or the control function. In comparison to other neural networks, CMAC has the advantage of very fast learning and it has the unique property of quickly training certain areas of memory without affecting the whole memory structure.

The network architecture of the CMAC is illustrated in Figure 2.8. The input data of every state variable are quantized into discrete regions and mapped on to different memory areas. Each indexed block memory called hypercube contains the input data of one quantized discrete state. The association memory mapping is implemented through hypercube to the actual memory as the mapping function of table look-up model. In addition to the association memory mapping function, the CMAC gives the feedback of the error of output to adjust the actual memory contents [1].

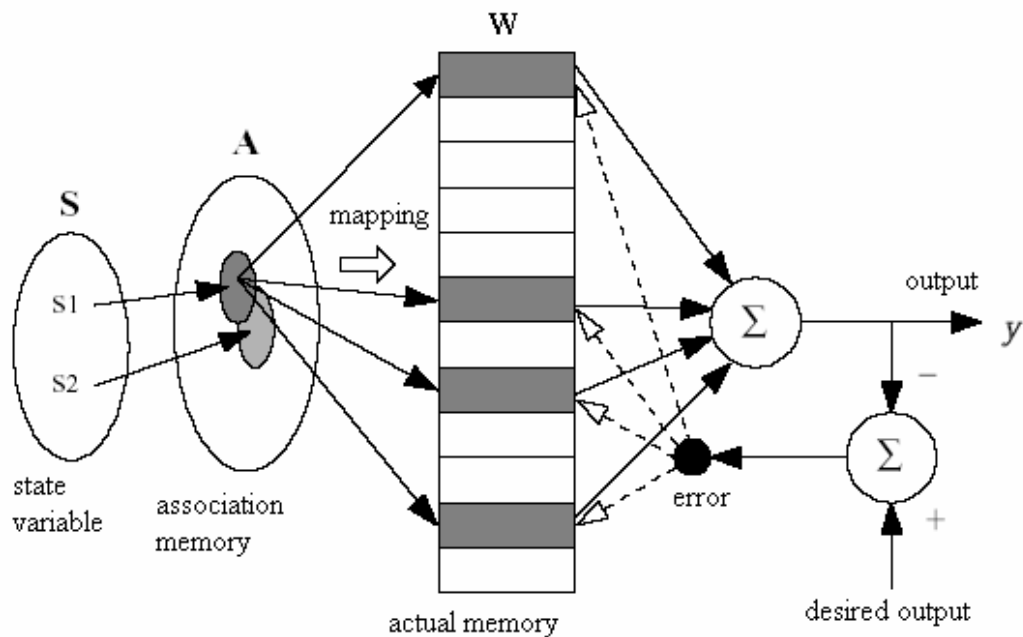


Figure 2.8 The learning architecture of CMAC

The output of this system is the summation of the contents of actual memory that is mapped by effective hypercubes. The error caused by the difference between the output summation and the desired output is processed as the feedback value for adjusting the contents of actual memory. The learning efficiency of CMAC system

depends largely on the division of hypercube. Its technique can be explained with Figure 2.9. This example has two state variables (s1 and s2) with each quantized into four discrete regions, called blocks. For instance, s1 can be divided into A, B, C and D and s2 can be divided into a, b, c and d. Areas formed by quantized regions, named as Bb, Gg, Kk, Oo are called hypercubes in the input state of (s1, s2) = (7,7). If the quantization for each variable is shifted by one element, different hypercubes will be obtained. For example, E, F, G, H for s1 and e, f, g, h for s2 are shifted regions. Ee, Ff, etc. are new hypercubes from the shifted regions. Each state is covered by N_e different hypercubes, where N_e is the number of elements in a complete block. There are 64 (= $4^2 \times 4$) hypercubes in this example. Each hypercube is taken as the corresponding address of actual memory element. And the data of each state will be distributively stored in memory elements associated with hypercubes that cover this state. Assume a_j represents an association vector of j^{th} input space ($j = 1, 2, 3 \dots N_s$) where N_s indicates the total number of input states. 99th input state (state (7, 7)) is used to explain the actual memory how to be mapped by an association memory. Figure 2.9 shows the state (7,7) is mapped by the hypercubes of Bb,Gg,Kk and Oo. If we give an index value for each mapped actual memory unit, then the state (7,7) can be mapped to the memory locations of 6,27,43 and 59. We can use an association vector shown as equation 2.6 to represent the mapping information.

$$\mathbf{a}_{99} = \begin{matrix} & a_6 & & a_{27} & & a_{43} & & a_{59} \\ [0 \dots 0 & 1 & 0 \dots 0 & 1 & 0 \dots 0 & 1 & 0 \dots 0 & 1 & 0 \dots 0]_{1 \times 64} \end{matrix} \quad (2.5)$$

$$\begin{matrix} \text{Bb} & \text{Gg} & \text{Kk} & \text{Oo} \end{matrix}$$

This is a 1×64 vector because there are 64 hypercubes needed (i.e. 64 actual memory units are used) in this case. In this vector, four 1's represent the mapped actual memory units that are used under this input state, and other 0's represent the mapped actual memory units are not used. Therefore, the locations of 6,27,43 and 59 are recorded as 1 and everything else is recorded as 0. The actual output y_{99} of input state (7,7) can be represented as:

$$y_{99} = \mathbf{a}_{99} \cdot \mathbf{w} \quad (2.6)$$

where w indicates the weight vector of actual memory contents.

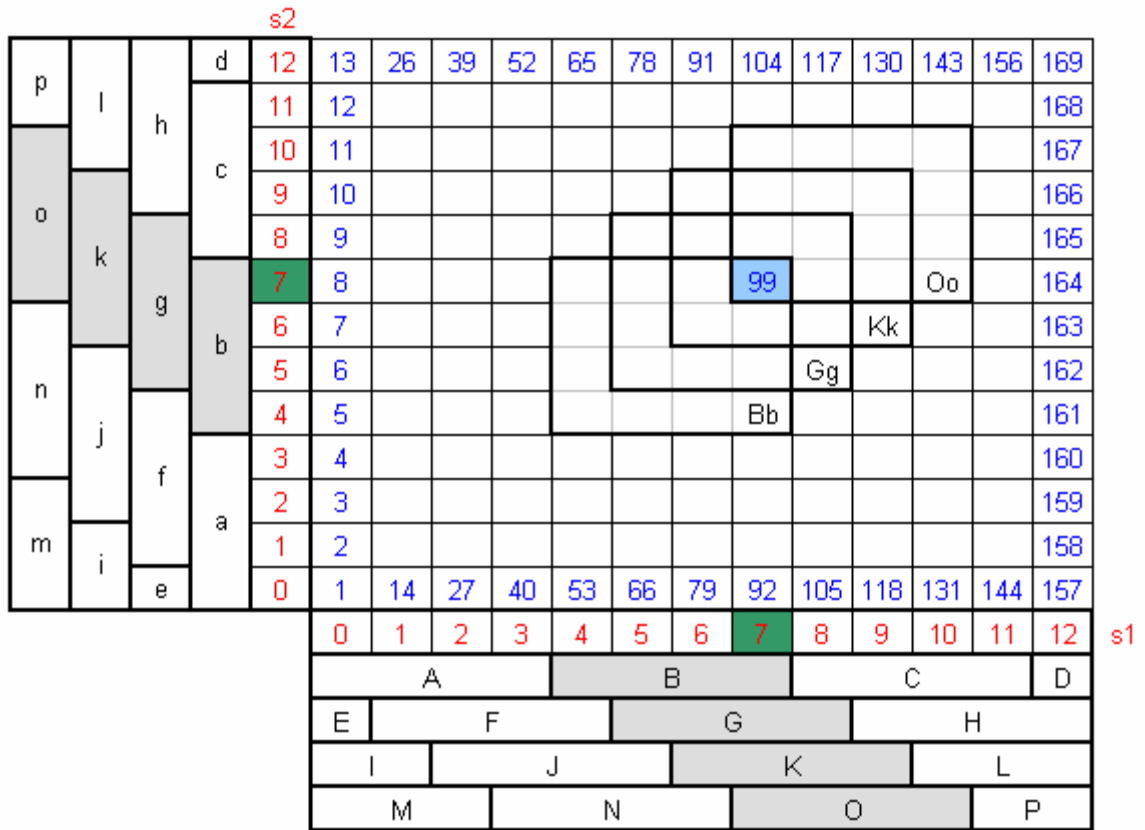


Figure 2.9 Block division of CMAC for a two-variable example

Since there are total of 169(=13x13) input states in this case, the association memory matrix can be represented as a 64 x 169 matrix shown as A matrix in equation 2.7. If we consider all corresponding outputs of input states, then the actual outputs can be represented as:

$$\mathbf{y} = \mathbf{A} \cdot \mathbf{W} = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_{169} \end{bmatrix}_{169 \times 64} \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_{64} \end{bmatrix}_{64 \times 1} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{64} \end{bmatrix}_{169 \times 1} \quad (2.7)$$

where \mathbf{y} indicates the vector of actual output, \mathbf{A} indicates the association matrix and \mathbf{w} indicates the weight vector of actual memory. CMAC requires 10816 (= 169 x 64) association memory units to record the information and requires 64 (= 64 x 1) actual memory units to record the weight information on this case.

Every step of CMAC operation is defined in Chapter 3. Chapter 3 is also a guide for writing a CMAC code in MATLAB environment.

CHAPTER 3

CMAC PROGRAMMING

This chapter includes programming details of the CMAC in the MATLAB environment and function approximation examples in order to analyze the effects of the CMAC parameters to the learning and learning convergence. There are not so much detailed explanations about CMAC programming in the literature. Authors who studied CMAC, preferred to explain the network structure based on mathematical neural form. From another point of view the CMAC is a look-up table as well. And during the programming phase, this perspective is useful to better understand the inner mechanism of this network

3.1. The CMAC Mapping

The input space is quantized into a number of intervals according to the generalization width. The distance among the input dimension of each interval is equal to the generalization width. Quantized region of the input space is called a layer. New layers can be added by shifting the intervals as shown in Figure 3.1, which is an example for one-dimensional CMAC.

-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
A					B					C					D					
E	F					G					H					I				
J		K					L					M					N			
O			P					R					S					T		

Figure 3.1 An example for quantized layers of the input space

The input space is defined between -5 and 14 , the generalization width is equal to 5 and there are four layers. Each layer can be modeled as a vector by shifting such as;

$$\begin{array}{ll} \text{Layer 1} & L1 = [-5 \ 0 \ 5 \ 10], \quad \text{Layer 3} \quad L3 = [-5 \ -3 \ 2 \ 7 \ 12], \\ \text{Layer 2} & L2 = [-5 \ -4 \ 1 \ 6 \ 11], \quad \text{Layer 4} \quad L4 = [-5 \ -2 \ 3 \ 8 \ 13]. \end{array}$$

A, B, C ... are the hypercubes that contain the weights. The hypercubes are numbered as, “A = 1, B = 2, C = 3, ... , T = 19” and the CMAC memory is formed from 19 memory locations. An address function is needed to map the input values into the memory locations.

The function, $\text{MAX} (\text{FIND} (L_i \geq x))$ where “MAX” and “FIND” are the MATLAB commands, gives the hypercube number in the i^{th} layer. For example, for the input $x = 3$, in the first layer, $3 \geq -5$ and $3 \geq 0$. The command, $\text{find} (L1 \geq 3)$ gives the vector $[1 \ 2]$ and $\text{max} ([1 \ 2])$ is equal to “2”. It means that the input $x = 3$, activates the 2nd hypercube “B” in the first layer and similarly G, L and R in the other layers as seen in Figure 3.2.

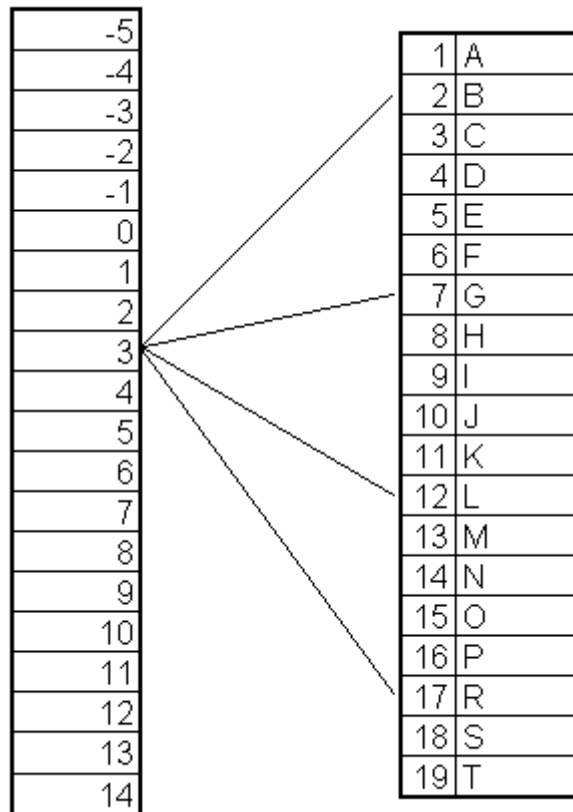


Figure 3.2 Single point mapping for one-dimensional CMAC.

The input ($x = 3$) is mapped on the memory locations of 2, 7, 12 and 17. The output for the input $x = 3$ is equal to the arithmetic sum of the weights in the hypercubes B, G, L and R. There is a two-dimensional mapping example shown in Figure 3.3.

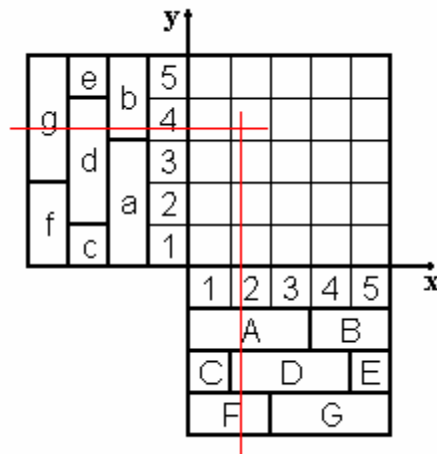


Figure 3.3 An example for two-dimensional CMAC

The input ranges are quantized similarly in the previous example. The input range is between 1 and 5 for both dimensions, and the hypercubes are; Aa, Ab, Ba, Bb, Cc, Cd, Ce, Dc, Dd, ... , Ff, Fg, Gf, Gg. They are numbered as; Aa = 1, Ab = 2, ... , Gg = 17.

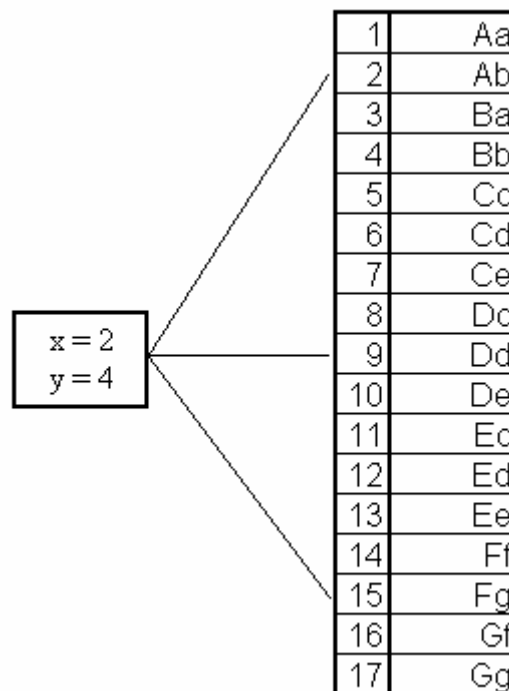


Figure 3.4 Single point mapping for two-dimensional CMAC.

The input ($x=2$ and $y = 4$) is mapped on the memory locations of 2, 9 and 15. Thus, the CMAC memory has 17 memory locations. For the input $x = 2$ and $y = 4$: the weights in the hypercubes Ab, Dd and Fg are activated and it is displayed in Figure 3.4.

Briefly, CMAC mapping method is practiced in two steps. First, find out which hypercubes are used in each layer and secondly give each hypercubes a number that is its address index in the memory. The n^{th} dimensional CMAC has the same mapping algorithm. While writing a CMAC code it is useful to create a subroutine that maps the input values to its memory locations. This subroutine may be a function where its inputs are the input dimension, input ranges, generalization width and total layer number and its outputs are the hypercube indexes or the memory address indexes.

3.2. The CMAC Training

CMAC training is the data storage of the memory. Initially all the memory locations are empty, it is to say all of the weights are equal to zero. The output for the desired point in the input space is the sum of the selected weights that are determined by the mapping. And the training procedure is:

1. The function F will be computed by the CMAC. The desired value of the output for each point in the input space is $Y = F (X)$.
2. A point X is selected in the input space where Y is to be stored. The current value of the function at that point (initially it equals to zero) $y = f (X)$ is computed.
3. Δ_i is added to every weight to produce y_i

$$\Delta_i = \alpha \frac{Y_i - y_i}{|L|} \quad (3.1)$$

where,

$|L|$ is the total number of layers and α is the learning rate.

Working with matrices and vectors in the MATLAB programming language facilitates the data storage operation. After the hypercube indexes are determined a vector of address indexes of the memory is obtained.

For the i^{th} training point, the output is $Y(i) = \text{sum}(M(\text{address}(:)))$ where, “M” is the memory vector and “address” is the vector of the address indexes and

$$M(\text{address}(:)) = M(\text{address}(:)) + \alpha (Y(i) - y(i)) / A.$$

After all the points in the input space are trained, this loop is repeated for the same points until the memory elements converge.

There are three cases:

1. Memory elements change periodically after a cycle.
2. Memory elements remain constant after a cycle.
3. Instability.

Convergence is gained in two ways. The memory elements remain constant after a certain cycle or the memory elements have the same values periodically. In which cycle, the elements converge, depends on the CMAC parameters, selected training points and the chosen size of the memory. If there are no learning interferences between the training points and if hash coding is not used, the memory elements converge at the first cycles. Very high learning rates may result in instability while very low learning results cause long convergence time. By using adaptive learning algorithms, the instability problem is solved [9].

Here the CMAC operation is described by using the Figure 2.9. Figure 2.9 displays a two dimensional CMAC. For instance, the input pairs are $s_1 = 7$ and $s_2 = 7$ and the target value $t = 4$. The input pairs s_1 and s_2 will activate the weights in the hypercubes Bb, Gg, Kk and Oo. There are 64 hypercubes in this example and the index numbers of Bb, Gg, Kk and Oo 6, 27, 43 and 59. After the first training the sum of these four weights in the hypercubes Bb, Gg, Kk and Oo will be equal to 4. Initially all the weights are equal to zero. So, each weight in these hypercubes will be equal to 1 in order to give the output 4.

For example, after the first training, to calculate the output for the input pairs $s_1 = 7$ and $s_2 = 8$ first the active weights must be found. These are Bc, Gg, Kk and Oo. The memory index of Bc is 7. The weight value in Bc was not active in the training so it remained zero. The output for $s_1 = 7$ and $s_2 = 8$ will be equal to the sum of the weights in Bc, Gg, Kk and Oo. Gg, Kk and Oo are equal to 1 and Bc is equal to 0 so the output is equal to 3.

3.3. Hash Coding

As the dimension of the CMAC network increases, the required size of the CMAC memory increases exponentially. After CMAC mapping, mapping the indexes into a smaller memory rather than the CMAC memory is a solution for the case of large memory requirements. Hash coding is used to solve this problem. The main idea is:

$$\text{index}_{\text{CMAC MAPPING}} = \text{MOD}(\text{index}_{\text{HASH MAPPING}}, \text{hash size}) \quad (3.2)$$

Formulation 3.2 causes different data mapped in the same memory address. This is called hash collisions. But usually, the errors due to the hash collisions are neglected with respect to the overall CMAC error. And choosing an appropriate hash size is important to minimize the errors due to the hash coding. One that gives smooth results is formulated below:

$$s = k \prod_{i=1}^n \left(\frac{I_i}{w} + 1 \right) \quad (3.3)$$

where,

s : hash size

I : input range

w : generalization width

n : input dimension

$k = 1, 2, 3, \dots$

Formulation 3.3 is used in the case of no learning interferences and it is displayed in Figure 3.5 for one-dimensional and in Figure 3.6 for two-dimensional input spaces. This basic sense can be applied for the n -dimensional input space. Here, the distance between two consecutive training points is equal to the generalization width. The training points are selected in this fashion.

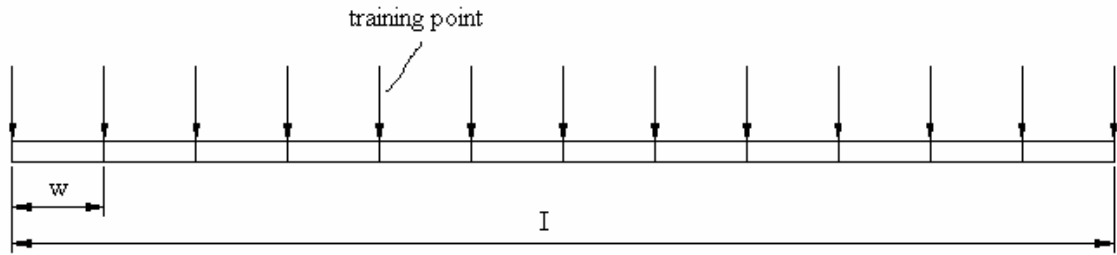


Figure 3.5 Selection of training points for hashing in one-dimensional CMAC

Linear hashing and uniform hashing are the other ways that can be applied to overcome the memory problem. In linear hashing, collisions are resolved by trying the next memory location in a linear sequence. In uniform hashing collisions are resolved by trying a random memory address.

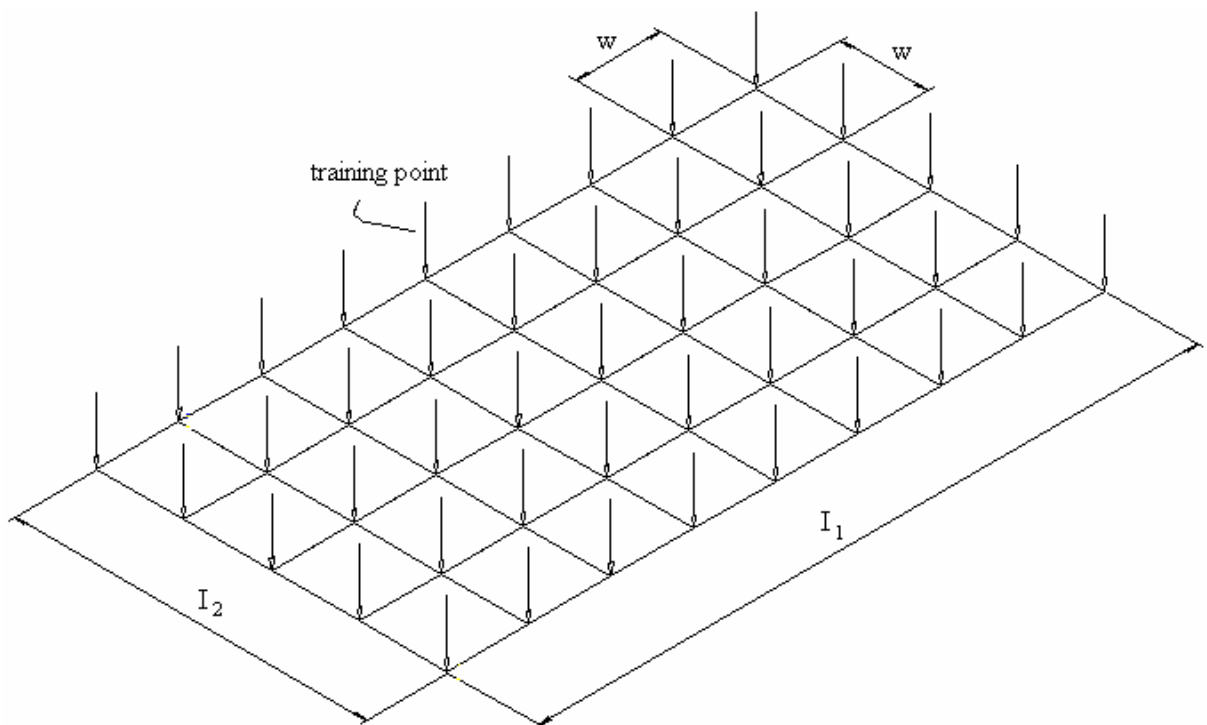


Figure 3.6 Selection of training points for hashing in two-dimensional CMAC

Hashing causes the memory to converge after a certain cycle, and the number of cycles to reach convergence is proportional to the input dimension. Hashing is necessary in the case of many degrees of freedom. In these situations, the required

memory with CMAC mapping may not be possible physically so hash coding is a must to solve this problem. During this study the hardware implementation is performed with the PC interface and the PC RAM is used for the CMAC memory. For the limited sized memory devices such as micro controllers, the hash coding algorithms help to use the memory capacity economically.

3.3. Function Approximation with the CMAC

CMAC is a good function approximator for both single and multi input functions. Albus, proposed CMAC to determine the control function of a robotic motion. Especially for the many degrees of freedom, it is hard to solve the analytic equations and sometimes it is not possible to model the physical properties of interactions like friction. Although all the terms of the equations of the motion are exactly found, solving these equations may not be so practical. Rather than kinematic solutions, referring to a table the output is calculated for the desired input values. Actually, CMAC determines the same equations of the motion by learning in an adaptive manner without any knowledge of the physical laws. That's what the human and the other mammals do while acting their motions. Some points in the input space is trained during training but by using the generalization property of the CMAC, the network gives output for every input point in the input range. This is the basic result of the idea "the similar inputs give similar outputs". Mathematically, generalization property is suitable to approximate to the continuous functions like motion control functions. If the generalization width is taken one, then the CMAC look-up table becomes a simple look-up table and the outputs of the points rather than the trained points remain zero. If the generalization width is too large, some overlaps will be formed. This overlaps causes the network to converge after many cycles and finally with an unacceptable error. If the generalization width is chosen approximately equal to the distance between the training points of the input space, a function with an acceptable error is obtained. Another parameter of the CMAC is the total number of layers. As the number of layers increases, output becomes more precise because more weights are used for output calculation since the number of weights is exactly equal to the number of layers used. Networks with more layers need more memory locations. Generalization width, number of layers, training point numbers are the key parameters for the function approximation. There is no criteria or formulation to optimize these parameters. Some

examples are shown here to see how the approximation changes with the parameters. These examples give an idea for the network architecture.

The sine function $\{ y = \sin (x), -180 \leq x \leq 180 \}$ is used as an example for the CMAC approximation. In the below tables, the output of the CMAC and the target function are plotted in the first figure. Next figure represents the convergence of the network.

The CMAC parameters like total layer number, generalization width, learning rate and training points are stated. The maximum error and the mean error of the CMAC output are calculated. Some graphs are introduced for optimum parameters.

In Table 3.1 total number of layers is equal to 10 and the generalization width is equal to 30. $\{-180, -150, -120, -90, -60, -30, 0, 30, 60, 90, 180\}$ are the training points. 130 memory locations are required and there is no hashing. The memory converges after the second cycle as seen in Figure 3.7.2 and the memory elements take the same values at every two cycles periodically. The learning rate is equal to 1 and remains constant during learning. The maximum error is 0.3084 and the mean error is 0.0917. Approximation results for this example are under the desired performance level.

The training points' set, $\{-180, -150, -120, -90, -60, -30, 0, 30, 60, 90, 180\}$ is represented in a MATLAB vector form as $(-180 : 30 : 180)$. In the memory convergence graph the vertical axis defines the sum of the memory elements. As it is mentioned before in this chapter, the convergence is obtained in two ways: the memory elements remain constant after a certain cycle or take the same values periodically after a certain cycle. In Figure 3.7.2 it is seen that the memory convergence like in the second way.

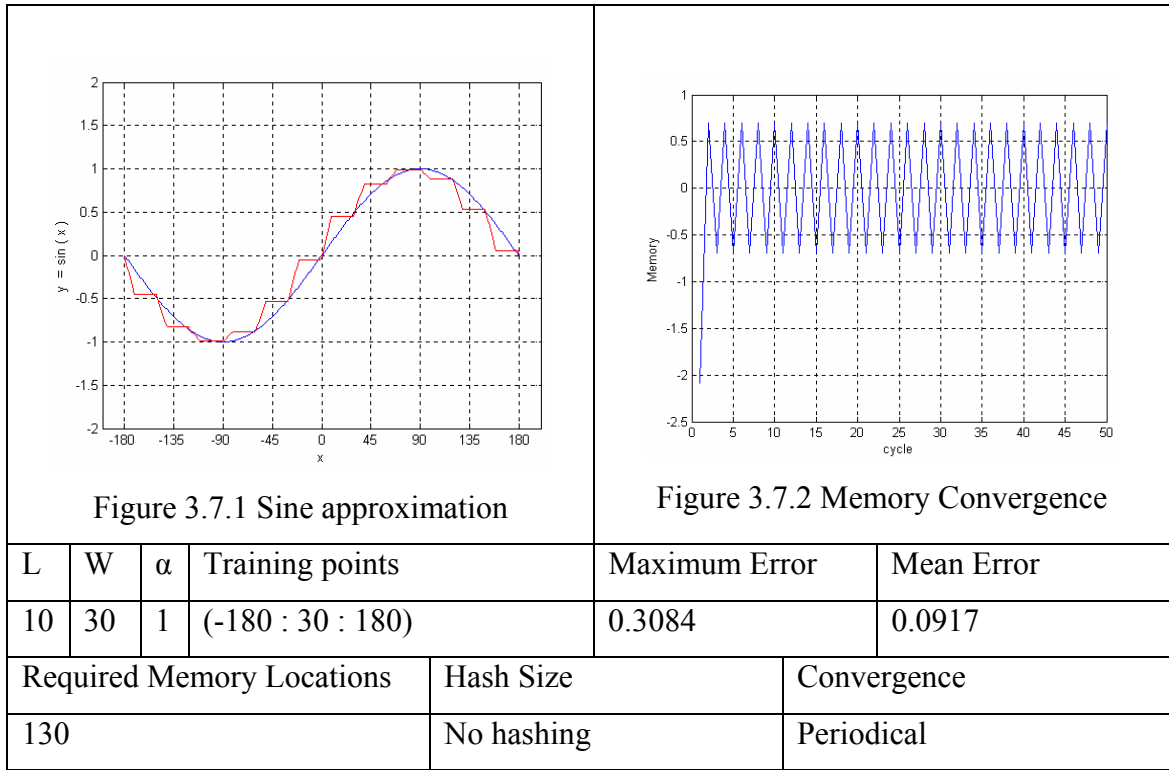


Table 3.1 CMAC parameters and sine approximation results

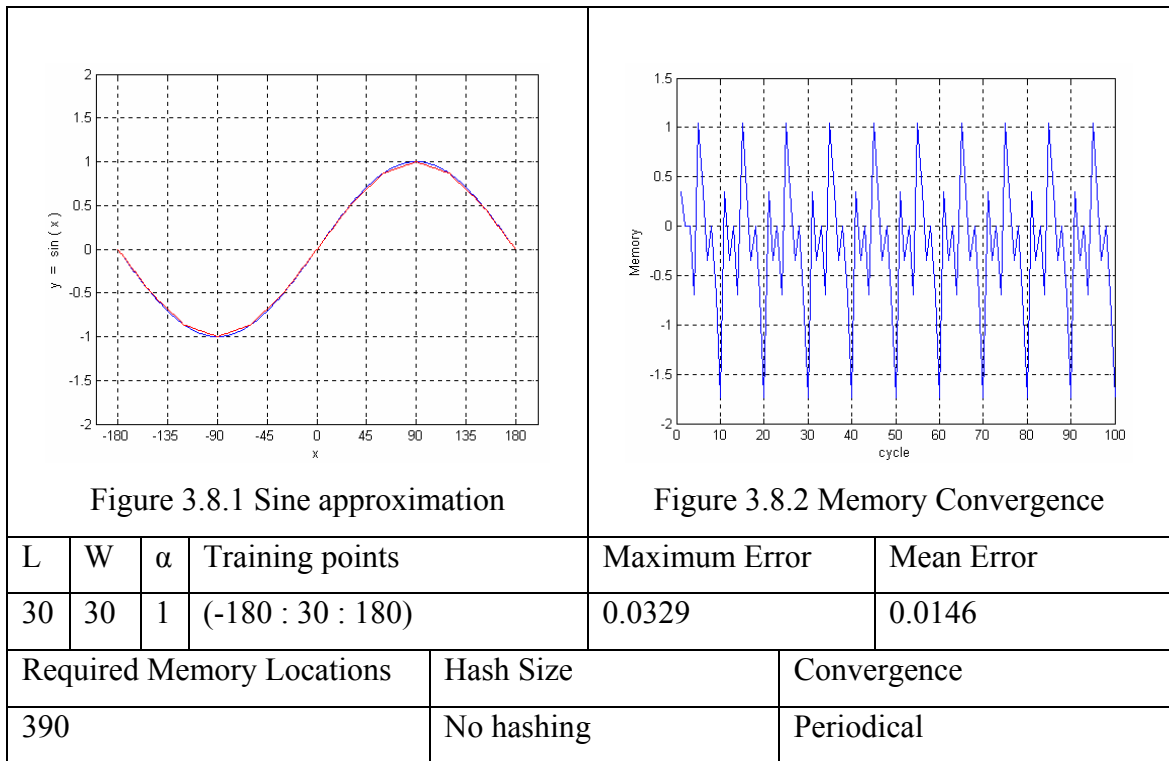


Table 3.2 CMAC parameters and sine approximation results

In Table 3.2 the total number of layers is increased from 10 to 30 so the required memory locations are increased from 130 to 390. There is no hashing. The same points in the input space are used for training (-180:30:180). The maximum error is decreased from 0.3084 to 0.0329 and the mean error decreased from 0.0917 to 0.0146. After convergence is obtained, the memory elements take the same values for every 10 cycles periodically.

It is clear that the approximation is better than the previous one in Table 3.1. While the training points and the generalization width are the same with the example in Table 3.1, the total number of layers is increased from 10 to 30 and a better approximation is gained. Also it is seen that more memory locations are needed as the convergence characteristic of the memory is changed. So, the total number of layers affects the approximation performance and it has a direct effect on the memory.

The total layer number and the maximum error relations are seen in Figure 3.9 and the total layer number and mean error relations are seen in Figure 3.10. Other parameters are the same with the examples in Table 3.1 and Table 3.2. Training points are (-180:30:180), without hashing. The generalization width is 30 and learning rate is equal to 1.

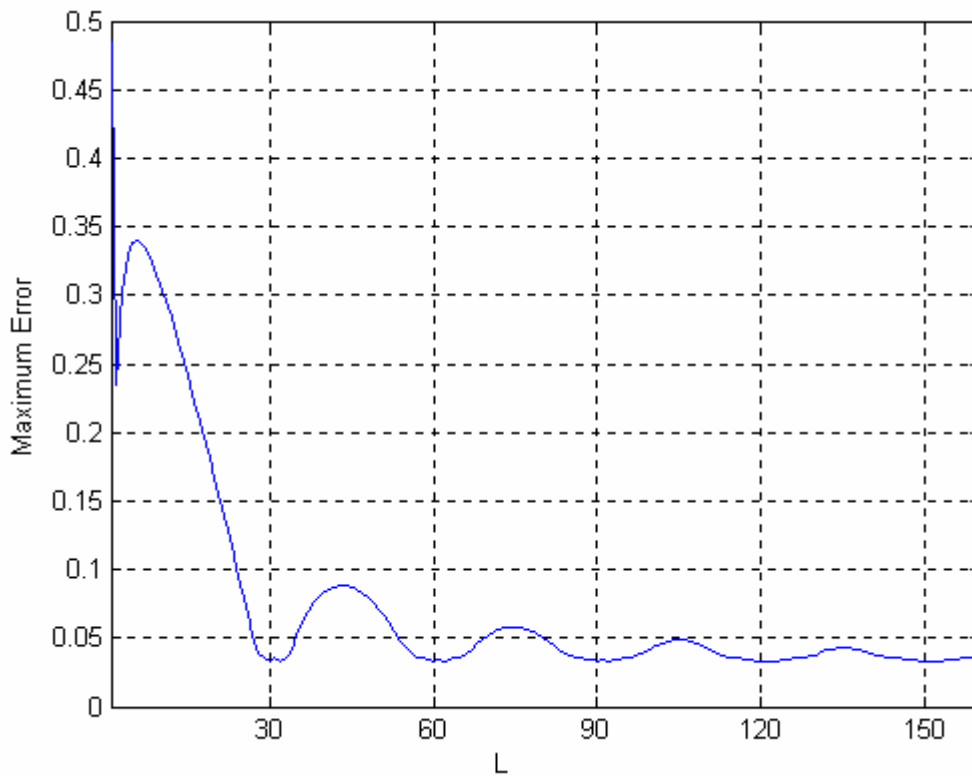


Figure 3.9 Maximum error – total number of layers. (w=30)

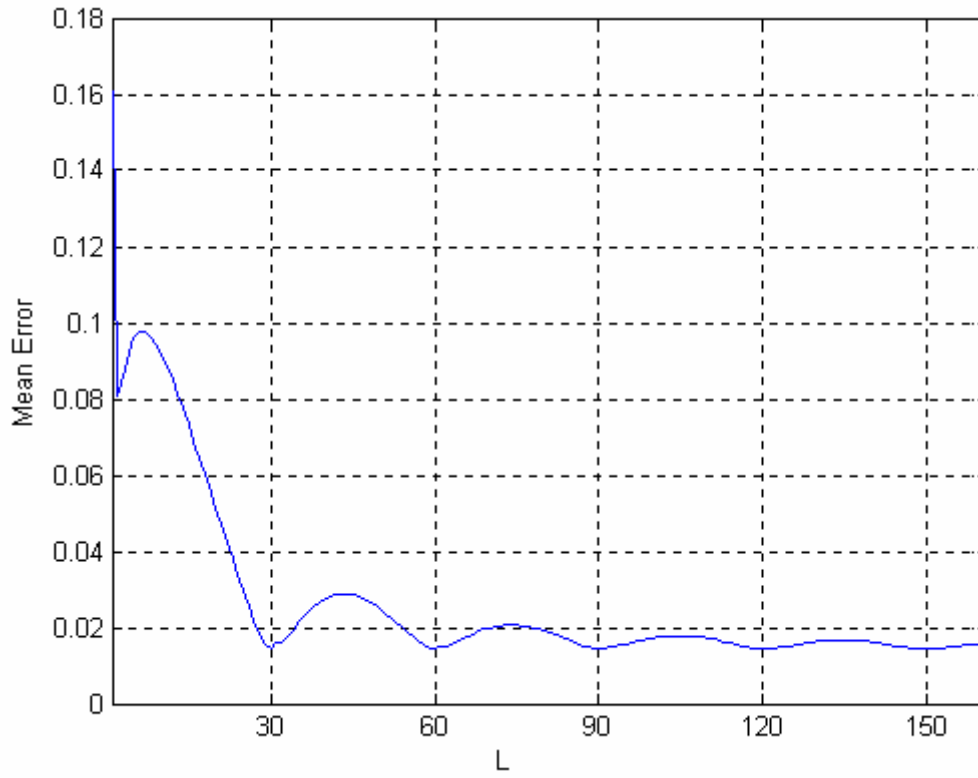


Figure 3.10 Mean error – total layer number ($w = 30$)

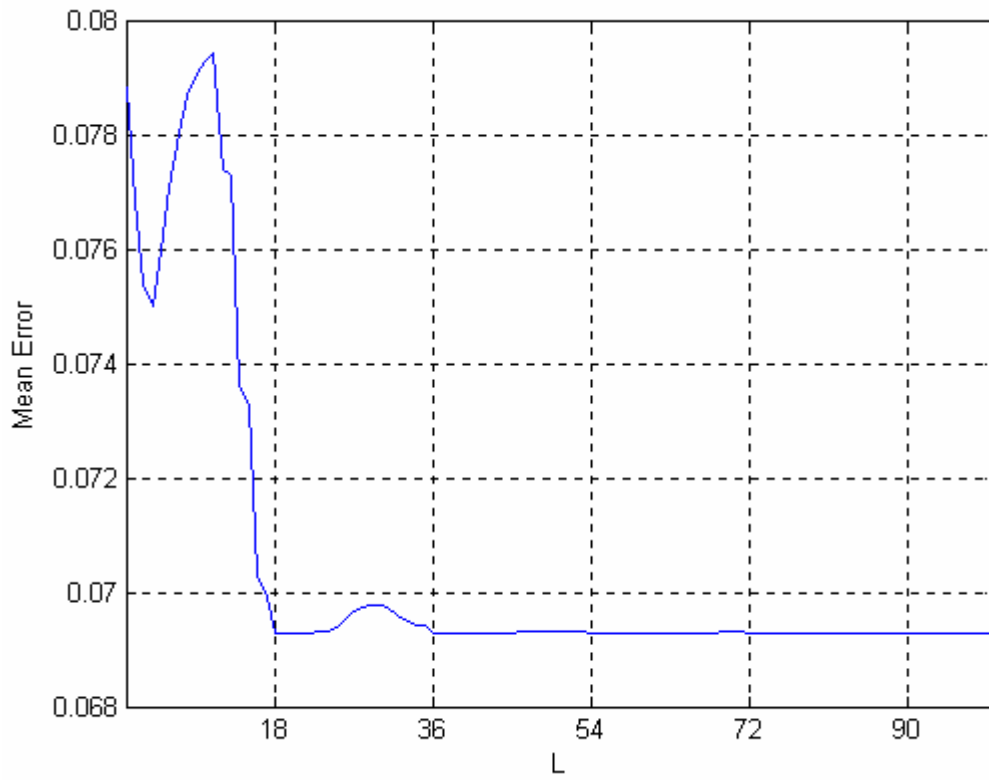


Figure 3.11 Mean error – total number of layers ($w = 18$)

It is clear that for $L < 30$, error values are high and the minimum points are periodically at 30, 60, 90, 120, 150, ... that are the multiples of 30.

Approximately,

$$L \approx k \cdot w \quad (3.4)$$

where, $k = 1, 2, 3, \dots$

The maximum error and minimum error are similarly affected with the total number of layers. In Figure 3.11 the same experiment was performed with 21 training points with no learning interference and where generalization width equals to 18. Figure 3.11 displays the relation of the mean error and total number of layers. The minimum error values are at points where total number of layers is equal to 18 and its multiples.

Choosing low L , is an advantage for less memory and fast computation and fast convergence. How many training points are used and training point locations affect the generalization width. And it is seen that the generalization width affects the total number of layers. And taking total number of layers equal to generalization width seems to be an optimum selection.

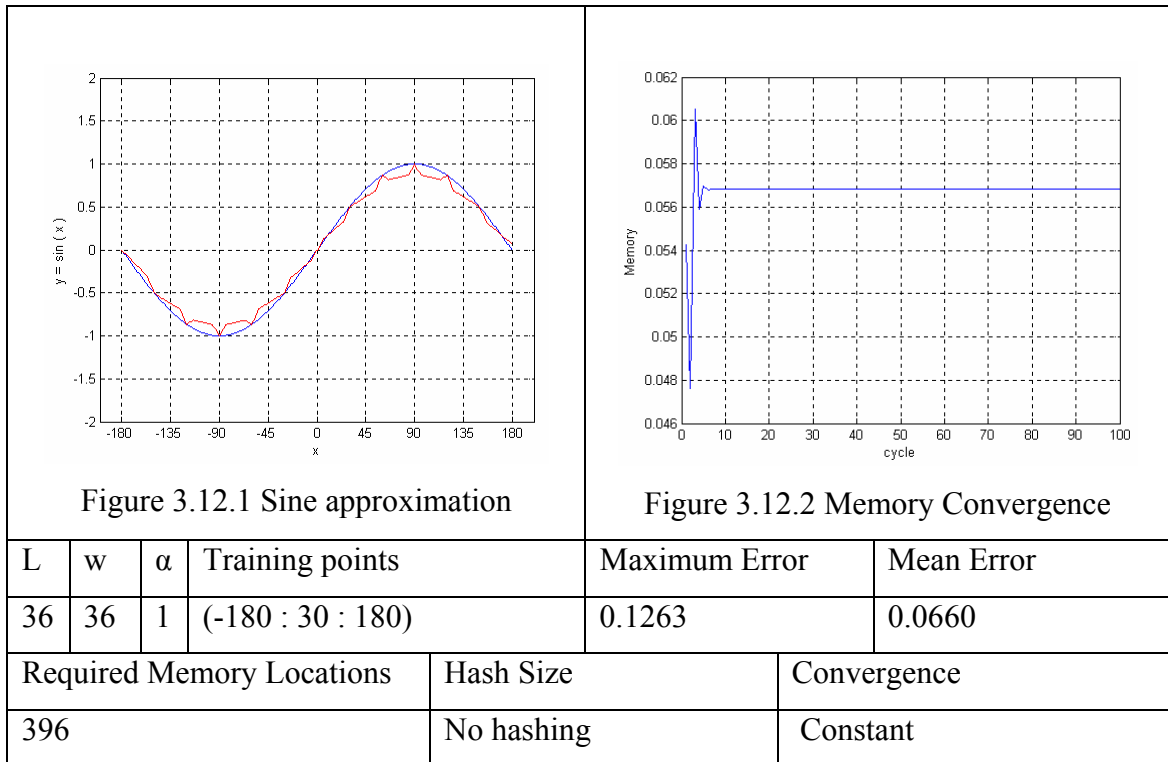


Table 3.3 CMAC parameters and sine approximation results

In table 3.3 the generalization width and the total number of layers are equal to 36. 396 memory locations are required and there is no hashing. The convergence is

obtained after 6 cycles and the memory elements remain at constant values as seen in Figure 3.12.2. The maximum error is 0.1263 and the mean error is 0.0660. The same training points $(-180 : 30 : 180)$ are used for training and it is seen that the error values are increased by increasing generalization width and total number of layers. In Table 3.3 by increasing the generalization width with constant training points, learning interferences form. Also by increasing training data with constant generalization width causes learning interferences. In Figure 3.12.1 it is seen that with increasing generalization width the error values also increase. Figure 3.13 and 3.14 show the relations between the error values and the generalization width. In these graphs the generalization width values are equal to the total number of layers. Each error value is calculated after convergence. Optimum results are obtained when $w = 30$. For $w < 30$ there are no learning interferences, but there are untrained gaps between two training points so the learning is insufficient. $w = 30$ is a boundary for learning interference. The mean error doesn't change dramatically for $w > 30$ but it is clear to choose $w = 30$ if the maximum error is taken into account.

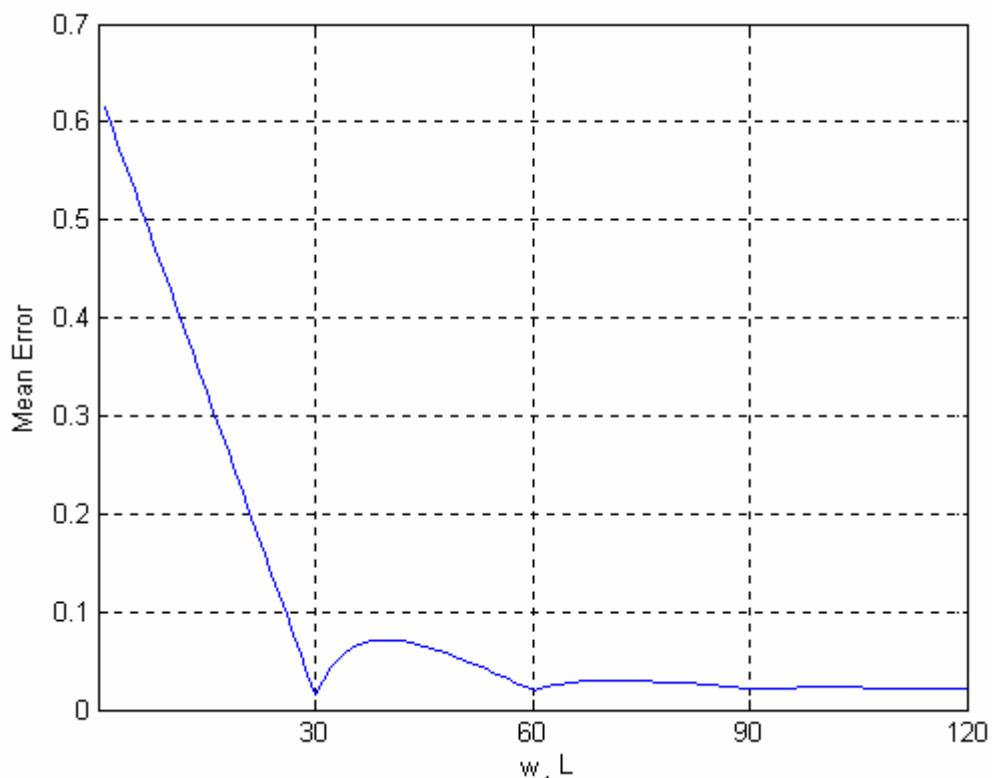


Figure 3.13 Mean error – total number of layers, generalization width training points $(-180 : 30 : 180)$

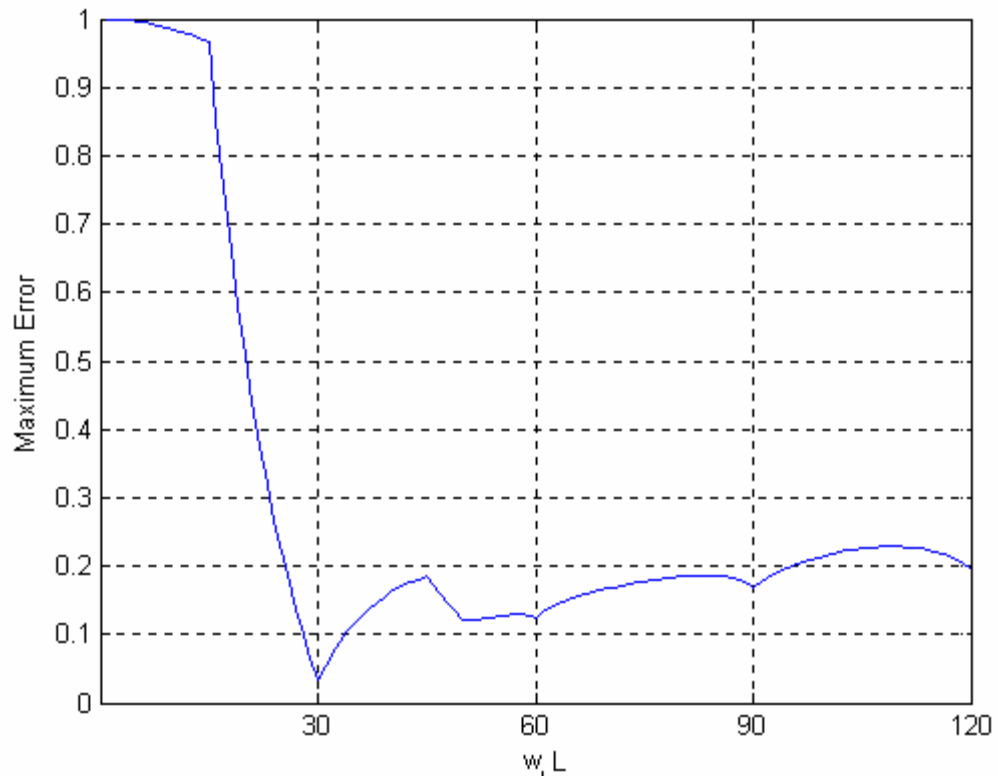


Figure 3.14 Maximum error – total number of layers, generalization width training points ($-180 : 30 : 180$)

Two training techniques are discussed in the literature, neighborhood sequential training and random training [6]. In neighborhood sequential training, there are no learning interferences like in the examples in Table 3.1 and 3.2. The training points are selected in a sequential fashion from -180 to 180 and the distance between two neighbor training points is equal to the generalization width. For the example in Table 3.3 the training points are selected sequentially but the distance between two neighbor training point is not equal to the generalization width so this type of training is not neighborhood sequential training. The other type of training technique for CMAC is the random training. The training points are selected randomly. The selection of the training points affects the approximation performance. For uniformly distributed random numbers the resulting CMAC performance is in the desired level. The use of this technique minimizes the training errors [6].

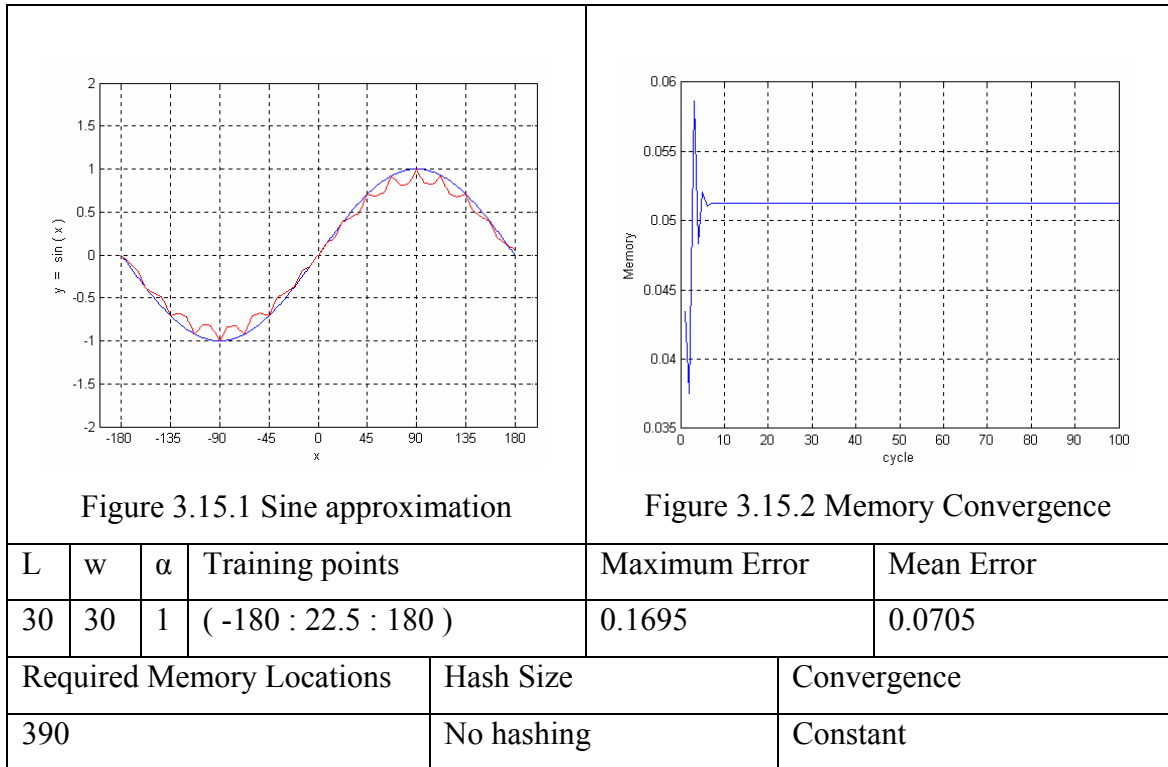


Table 3.4 CMAC parameters and sine approximation results

In Table 3.4 the generalization width and the total number of layers are equal to 30. 390 memory locations are required and there is no hashing. Maximum error is 0.1696 and mean error is 0.0705. The memory converges after 5 cycles and the memory elements remain at constant values.

When a CMAC is trained, the contents of all memory elements whose input points are in the same neighborhood of the training points are affected. If subsequent training input points are chosen in the same neighborhood as any previous inputs, then some memory elements are repeated and those that were adjusted by the previous training sessions will be improperly altered. This is termed learning interference [6]. And in the example in Table 3.4 although the same parameters are used the error values are increased with respect to the example in Table 3.2. The training points sequence created learning interferences in Table 3.4.

In neighborhood sequential training technique that is devised to avoid learning interference is to choose training input points that lie just outside of the neighborhood of the previous training input point. No learning interference occurs in this training technique like in the example in Table 3.2. In table 3.4 there are learning interferences so the output is under desired performance level.

In Table 3.5 the sequential neighborhood training technique is used and the output performance level is higher than the previous example. The generalization width and the total number of layers are equal to 15. 375 memory locations are required and there is no hashing. The memory converges after 2 cycles. The maximum error is 0.0084 and the mean error is 0.0036.

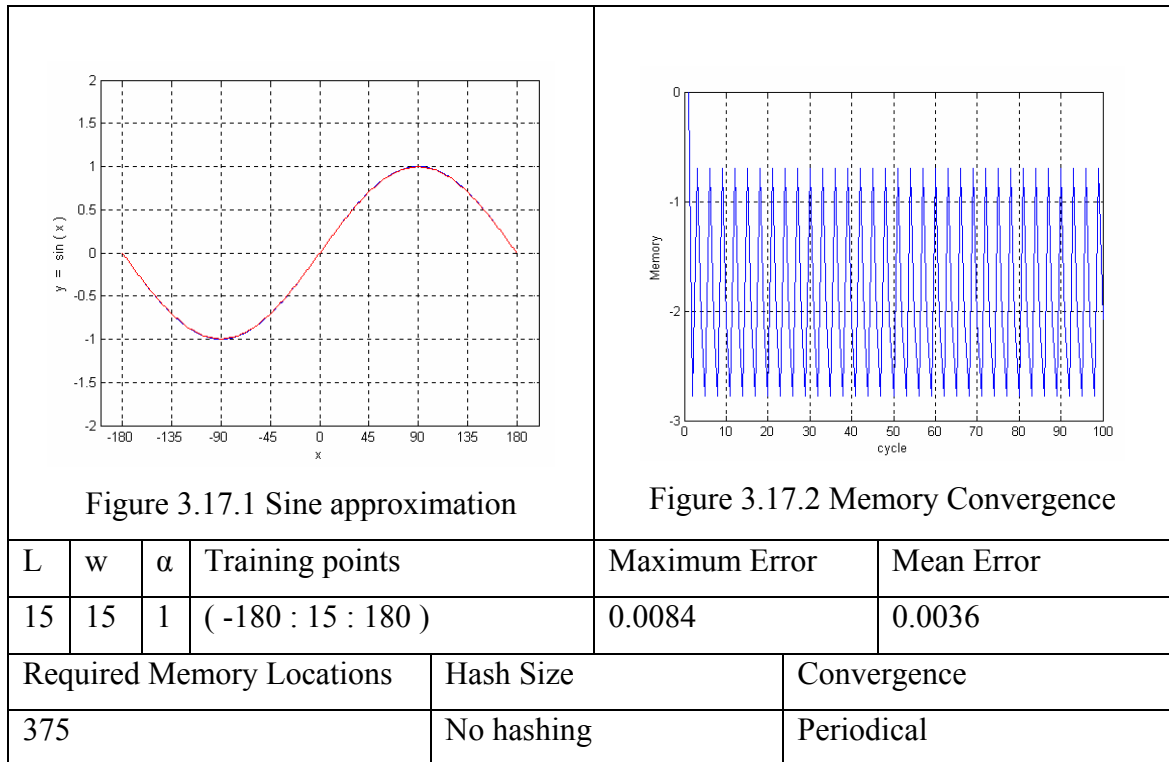


Table 3.5 CMAC parameters and sine approximation results

There are more training points in the example in Table 3.5 (-180 : 15 : 180) and the approximation performance is higher than the example in Table 3.2 (-180 : 30 : 180).

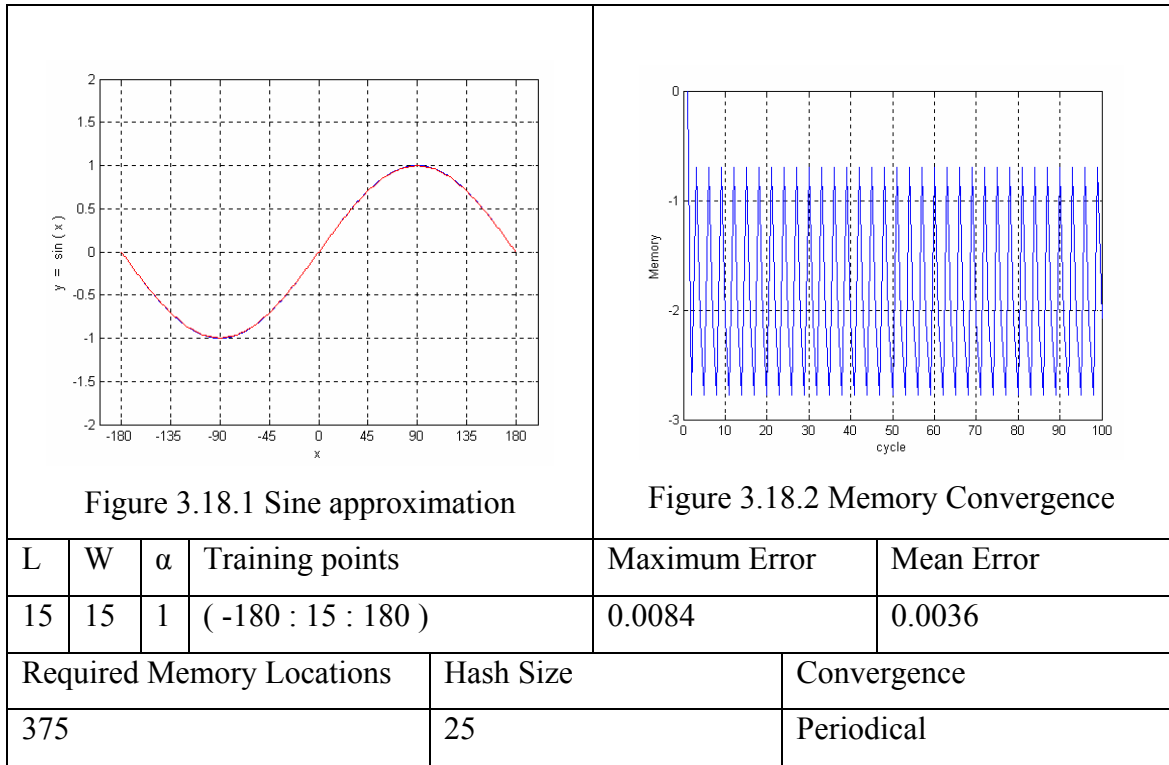


Table 3.6 CMAC parameters and sine approximation results

In table 3.6 the generalization width and the total number of layers are equal to 15. 375 memory locations are required. 375 memory locations are reduced to 25 memory locations by hash coding according to the formulation 3.3. Maximum error is 0.0084 and mean error is 0.0036. The memory converges. It is seen that all the parameters except the memory size are same with the example in Table 3.5.

The CMAC output error and hash size relation is seen in Figure 3.19 and 3.20. Figure 3.19 shows the relation between hash size and maximum error of the CMAC approximation. Figure 3.20 shows the relation between hash size and mean error of the CMAC approximation. The CMAC parameters are taken from Table 3.5 in for the graphs in Figure 3.19 and 3.20. It is seen that maximum error and the mean error affected similarly with hash size. The example in Table 3.6 is trained in neighborhood sequential training technique which is also illustrated in Figure 3.5 and Figure 3.6. In the example in Table 3.6 the hash size is selected according to the formulation 3.3. The graphs in Figure 3.19 and 3.20 prove formulation 3.3. This formulation gives high performance results with neighborhood sequential training.

If the training points are selected according to the neighborhood sequential training technique, the formulation 3.3 can be used to evaluate the hash size. It is seen in

the graphs in Figure 3.19 and 3.20 good results are obtained at 25 and its multiples. In this example the required memory locations are reduced to 25 from 375 and the performance of the approximation did not change in sine approximation example. In the case of multi-dimensional CMAC networks hashing is very useful to use less memory space. But in this hashing algorithm the training points and hash size must be selected very carefully else the error values increases as shown in the graphs in Figure 3.19 and 3.20. For instance if the hash size is 150 the mean error is approximately 0.004 while mean error is over 0.6 if the hash size is 188.

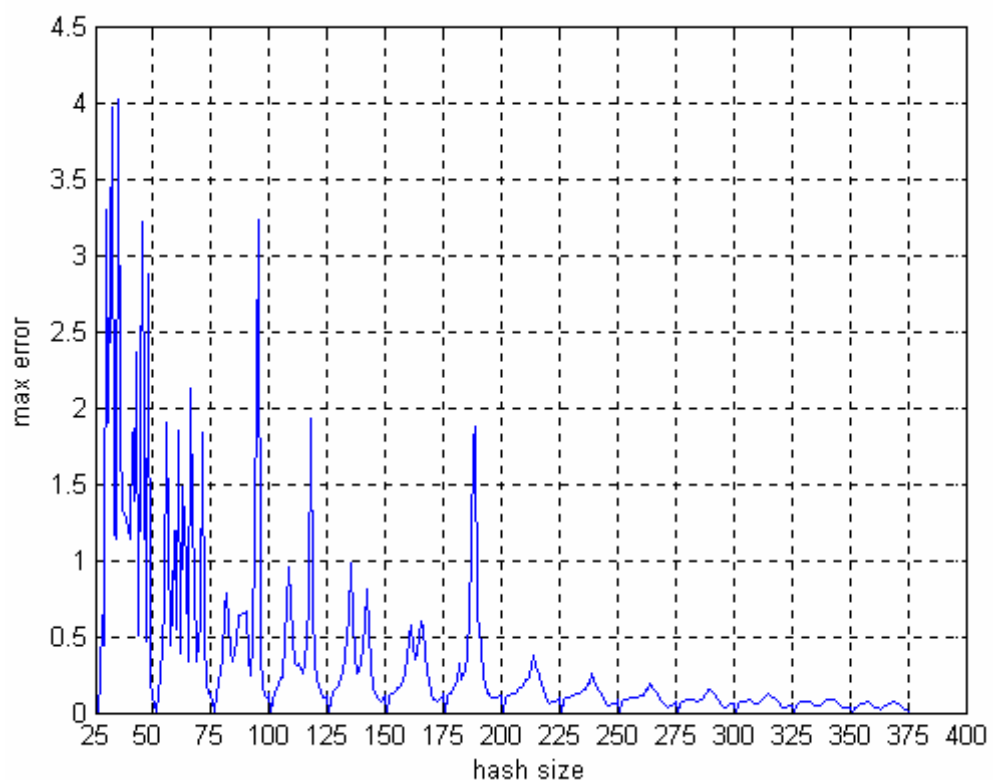


Figure 3.19 Hash size – maximum error

One dimensional function approximation of CMAC

where training points set $(-180 : 15 : 180)$ and $L = 15, w = 15$

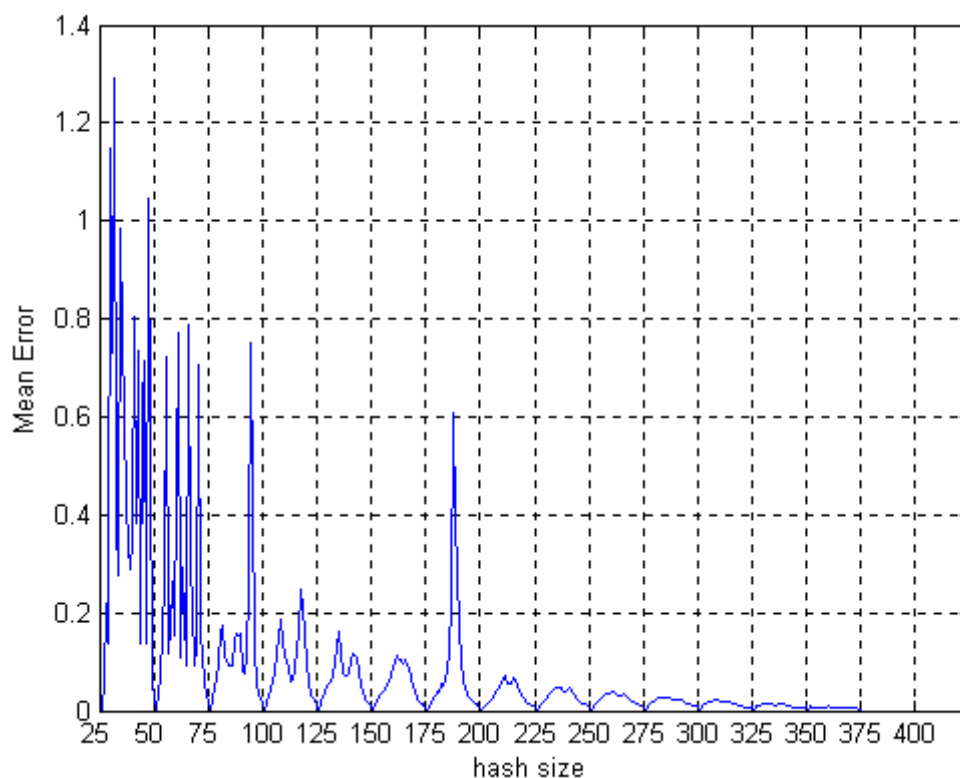


Figure 3.20 Hash size – mean error

One dimensional function approximation of CMAC
 where training points set $(-180 : 15 : 180)$ and $L = 15, w = 15$

In the example in Table 3.7 the training points are selected randomly at 43 points. Total number of layers and generalization width is 55. The learning rate is equal to 1. 415 memory locations are required and there is no hashing. Memory converges after 100 cycles and the memory elements remain at constant values. Maximum error is 0.0861 and mean error is 0.0189. It is seen that in graph in Figure 3.211 there are untrained regions between points -135 and -90 and between 75 and 105 . The training point set for this example is $\{-143 -126 70 14 107 97 -114 129 -65 31 -175 -66 -127 85 7 -140 32 104 162 -116 -165 -128 -79 87 17 66 -73 -68 24 -12 -55 -39 -33 -10 -44 -3 -94 111 30 -164 40 28 125\}$.

In the random training technique the convergence is gained after more cycles with respect to neighborhood sequential training technique. In the example in Table 3.20 the convergence is gained after 100 cycles while the convergence is gained in the first cycle in neighborhood sequential training technique. But the training point distribution is very important in random training technique. If there are no untrained gaps in the input space by the help of generalization the learning errors are minimized

after cycles while in the neighborhood training technique the learning errors do not change with cycles.

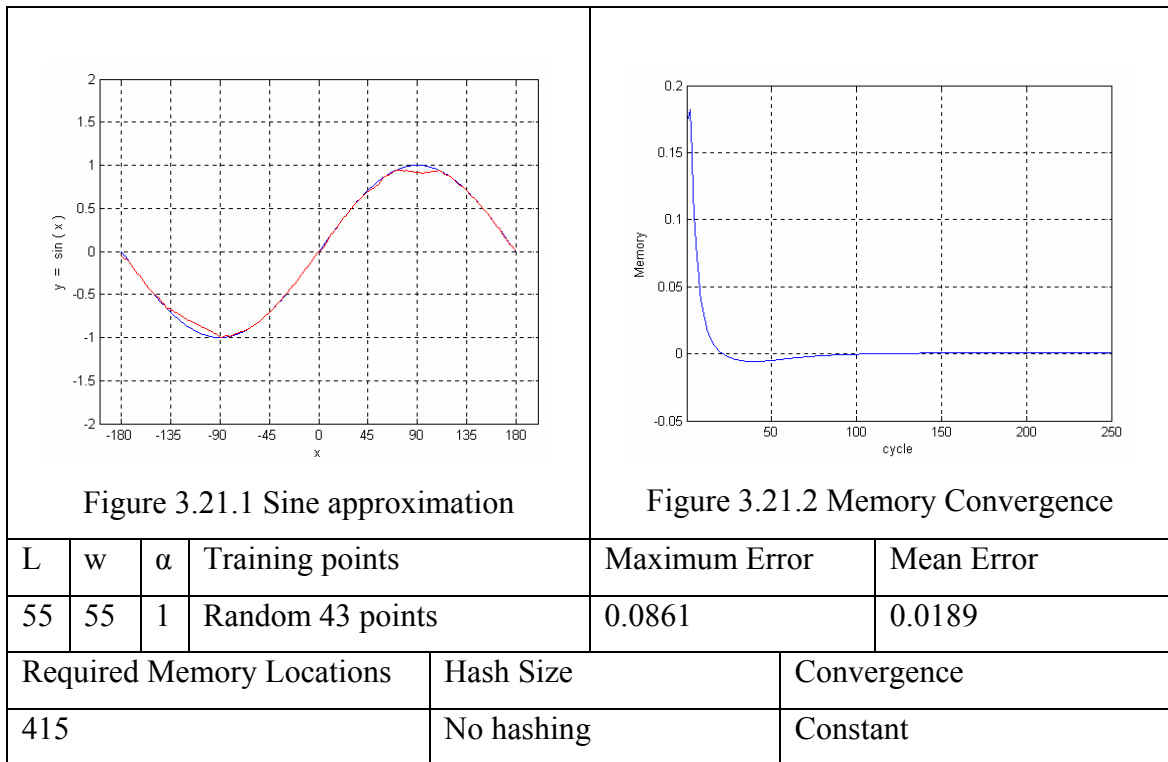


Table 3.7 CMAC parameters and sine approximation results

Figure 3.22 shows the relation between the total number of layers and CMAC output mean error. The CMAC parameters are equal to the parameters in the example in Table 3.7. Figure 3.10 shows that the total number of layers is affected with the generalization width. This relation is valid for neighborhood sequential training technique. In random training technique there is no such relationship. But in Figure 3.22 it is seen that the error values are low where total number of layers are higher than 20.

In Figure 3.23 and Figure 3.24 the generalization width changes with total number of layers. It is seen that for very high and low values the maximum error is high but the mean error does not change after a certain value where generalization width and the total number of layers are equal to 60. But in Figure 3.23 the maximum error increases with the increasing generalization width and total number of layers.

According to the total number of layers and the CMAC performance graphs, low total number of layers results in unacceptable approximations. On the other hand very high values of total number of layers cause high maximum errors. As a result,

convergence is slowed down. As the number of layers increases there are more loops in the program code so this makes slower learning and output calculation.

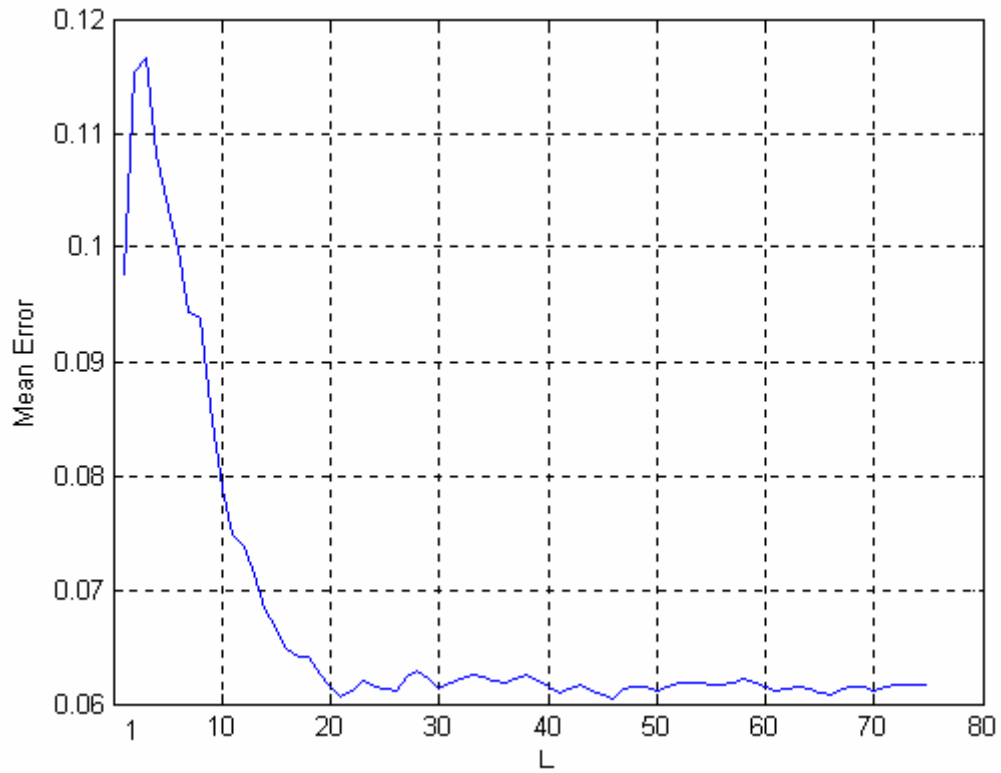


Figure 3.22 Mean error – total number of layers

w = 55, random training in 43 points

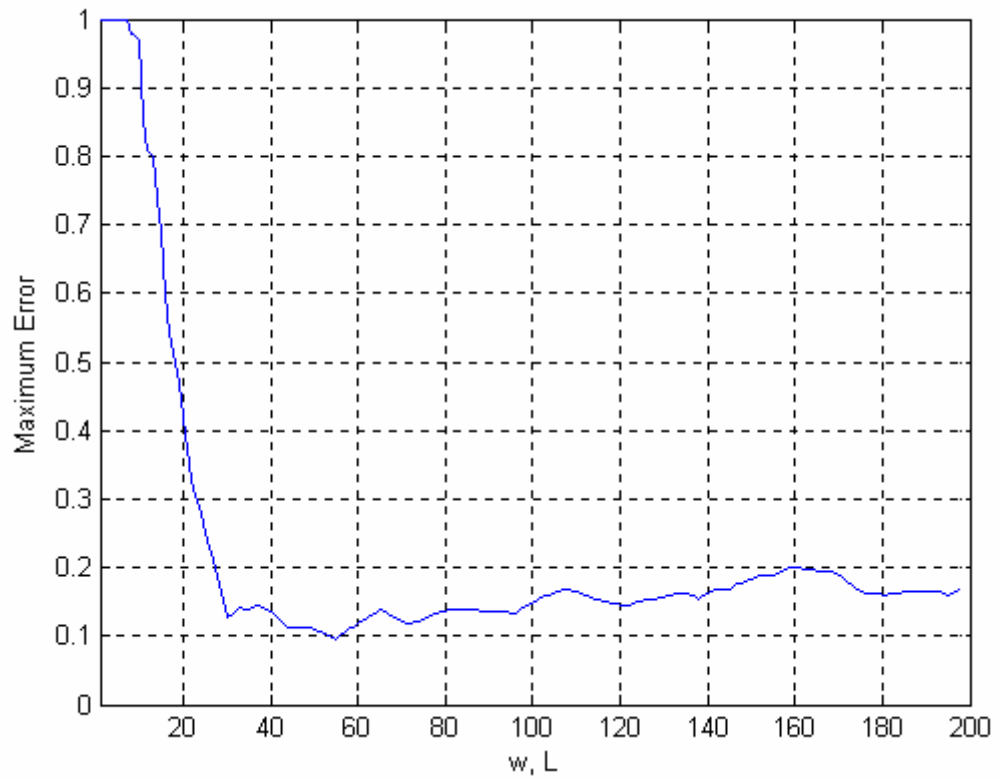


Figure 3.23 Maximum error – total number of layers
random training in 43 points

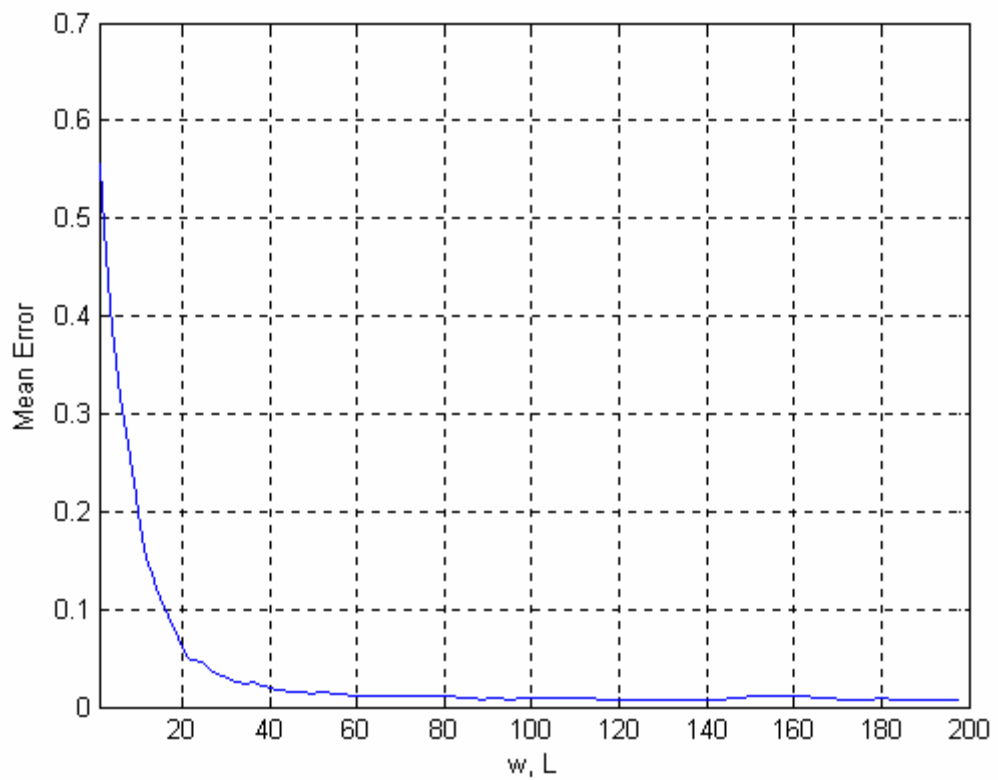


Figure 3.24 Mean error – total number of layers
random training in 43 points

In Table 3.8 the generalization width and the total number of layers is 55. The learning rate is equal to 1. The training points are randomly chosen and same with the example in Table 3.7. 415 memory locations are required. It is reduced to 200 memory locations by using hash coding. The maximum error is 0.0892 and mean error of the output is 0.0211. Convergence is obtained after 250 cycles. The number of cycles to reach the convergence is increased with hash coding. So it can be said that the random training technique and hash coding cause the convergence to be reached after more cycles than the situations with no hashing.

Generally, in neighborhood sequential training all memory elements are not addressed during training because some memory elements are not modified and remain zero. Hash size is reduced to very low values with respect to the required memory size of CMAC. But there is no such a relationship in random training technique. And the formulation 3.3 can not be used for estimating the hash size in the case of random training. Other hashing algorithms rather than the one applied to neighborhood training can be used for better approximation and low hash size values.

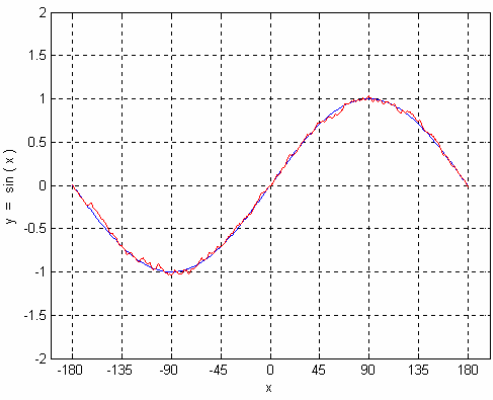
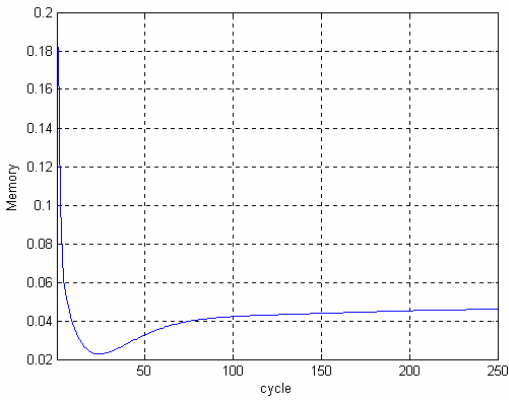
 <p>Figure 3.25.1 Sine approximation</p>				 <p>Figure 3.25.2 Memory Convergence</p>	
L	w	A	Training points	Maximum Error	Mean Error
55	55	1	Random 43 points	0.0892	0.0211
Required Memory Locations			Hash Size	Convergence	
415			200	Constant	

Table 3.8 CMAC parameters and sine approximation results

Two-dimensional CMAC examples are seen in Figure 3.26 and Figure 3.28. ($z = \sin(x) \cdot \cos(y)$). In Figure 3.26 the CMAC parameters are;

$w = 30, L = 30, \alpha = 1$, the sequential neighborhood training technique is used.

Results are:

Maximum Error = 0.0170, and mean error = 0.0056.

2510 memory locations are used.

Figure 3.26 the CMAC parameters are;

$w = 15, L = 15, \alpha = 1$, the sequential neighborhood training technique is used.

Results are:

Maximum Error = 0.0669, and mean error = 0.0221.

1470 memory locations are hashed into 49 memory locations. The convergence curves are seen in Figure 3.27 and 3.29. The hashing algorithm makes CMAC to converge after a certain number of cycles. In case of no hashing like the example in Figure 3.26 the memory elements converge at the first cycle. But as it is seen in Figure 3.29 the convergence is obtained after 250 cycles for the example in Figure 3.28. But if the memory requirements are taken into account and the convergence speed is less important than the memory capacity than hashing is very advantageous in that case.

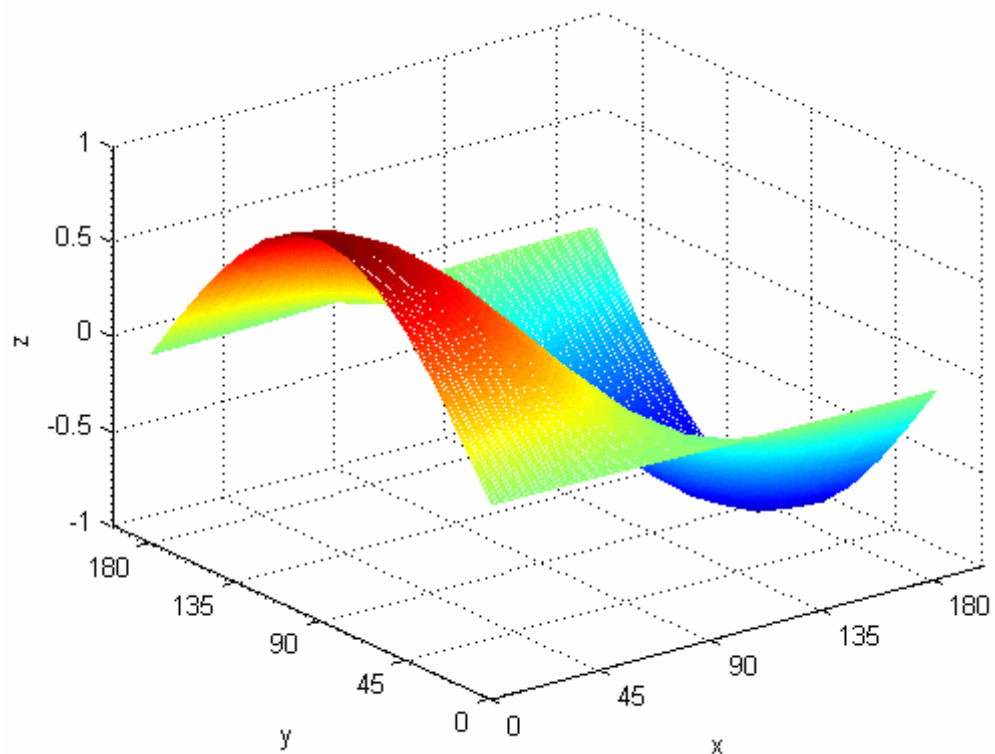


Figure 3.26 CMAC output for approximation of the function $z = \sin(x) \cos(y)$

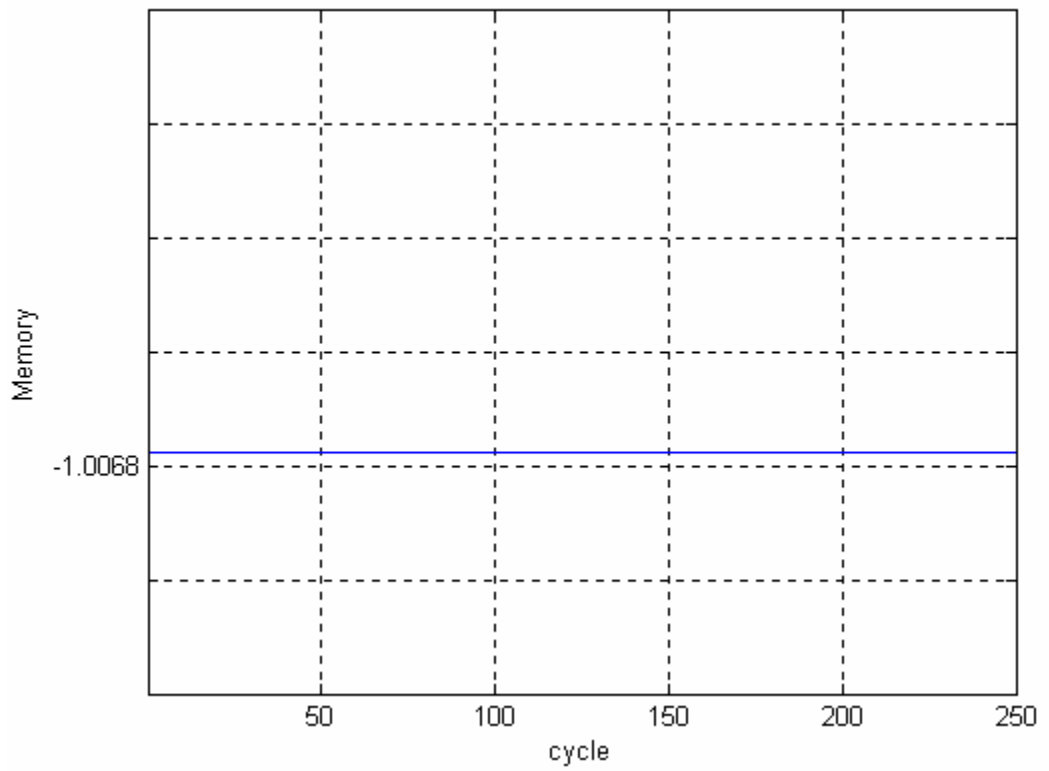


Figure 3.27 Memory convergence of two-dimensional CMAC

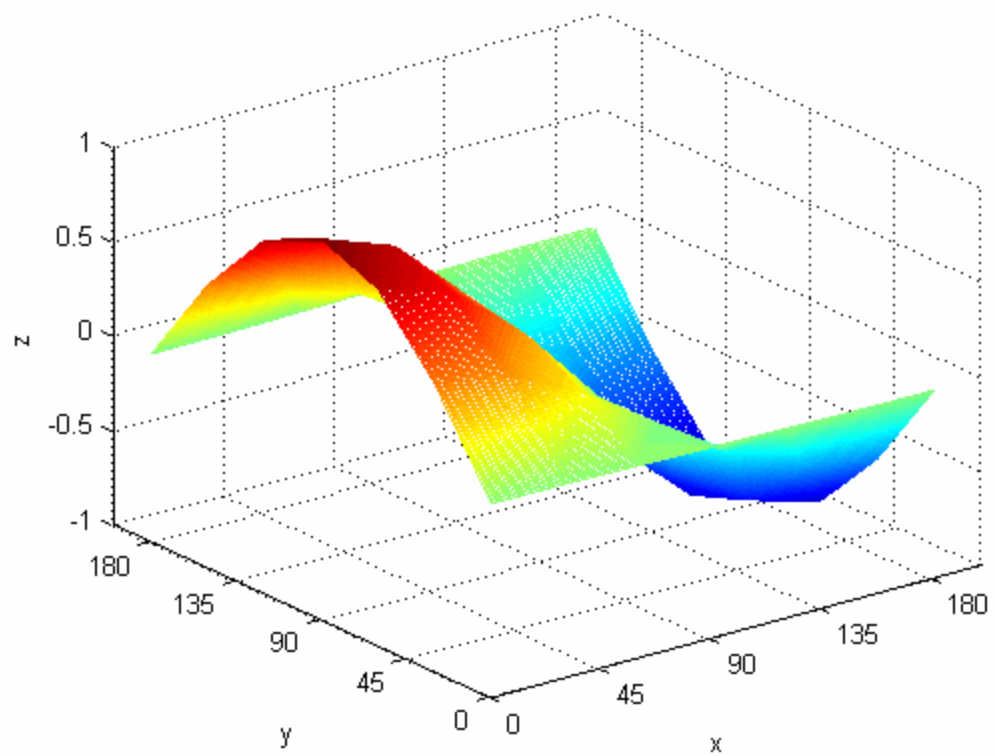


Figure 3.28 CMAC output for approximation of the function $z = \sin(x) \cos(y)$

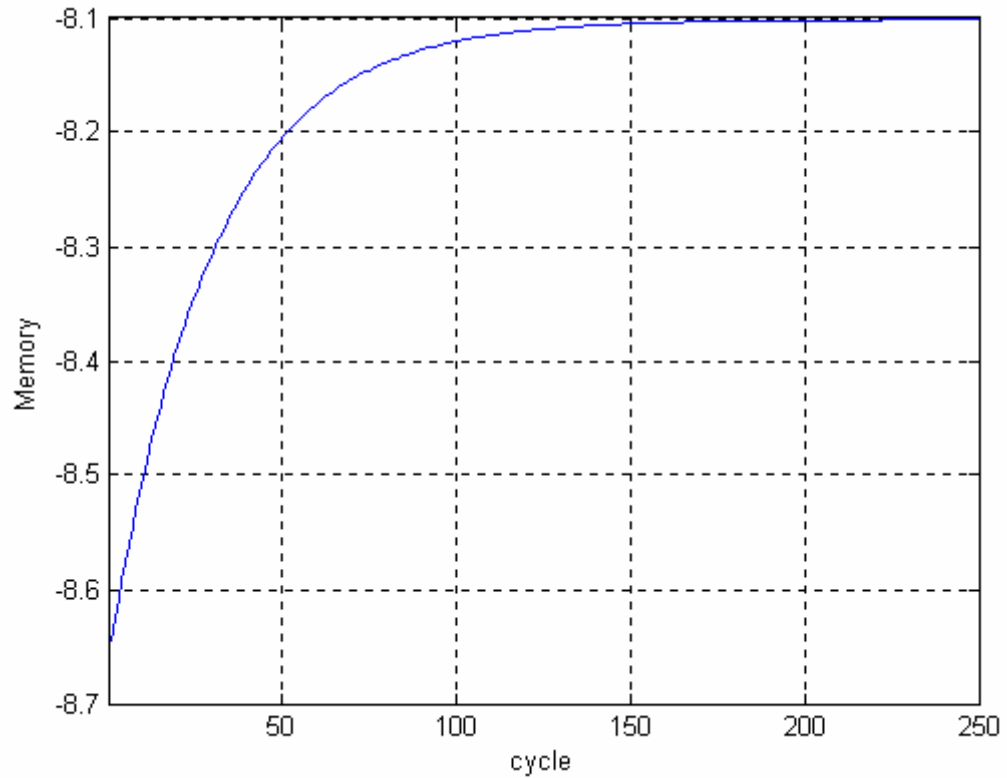


Figure 3.29 Memory convergence of two-dimensional CMAC

In Table 3.9 the generalization width and the total number of layers are equal to 15. 375 memory locations are required and there is no hashing. The learning rate is equal to 0.5. The maximum error equals to 0.0084 and mean error of the CMAC output is equal to 0.0036 like in the example in Table 3.5. The only difference is the learning rate between two examples in Table 3.5 and in Table 3.9. The convergence is obtained at the second cycle in the example in Table 3.5 where the learning rate is 1. But in the example in Table 3.9 the memory converges after 55 cycles as it is seen in Figure 3.30.2.

Another example is displayed in Table 3.10 with different learning parameters. The generalization width and the total number of layers are equal to 27. The learning rate is 0.1. 387 memory locations are required and hash coding is not used. The maximum error is 0.0639 and the mean error is 0.0326. It is seen in Figure 3.31.2 that the memory converges after 200 cycles.

Learning rate is a critical parameter for CMAC. While high learning rates causes instability, very low learning rates delay convergence. CMAC has an advantage of fast computation. Learning rate is the one of the parameters that affects convergence and computation time.

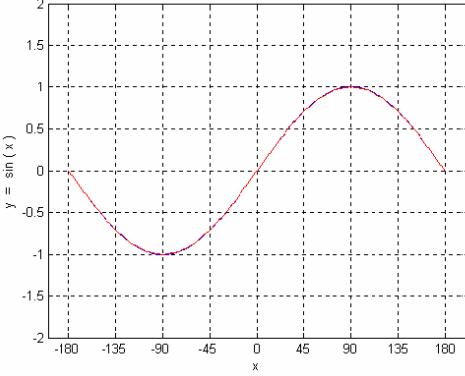
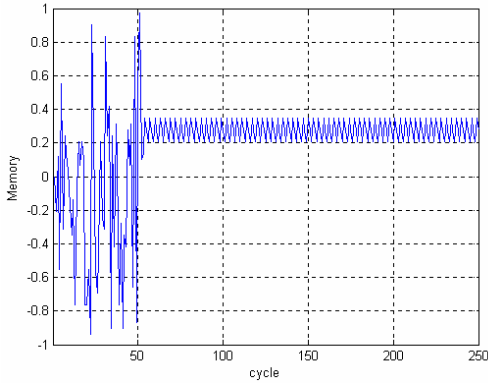
					
Figure 3.30.1 Sine approximation				Figure 3.30.2 Memory Convergence	
L	W	α	Training points	Maximum Error	Mean Error
15	15	0.5	(-180 : 15 : 180)	0.0084	0.0036
Required Memory Locations			Hash Size	Convergence	
375			No hashing	Periodical	

Table 3.9 CMAC parameters and sine approximation results

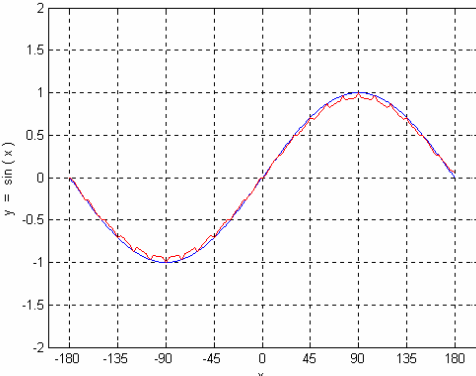
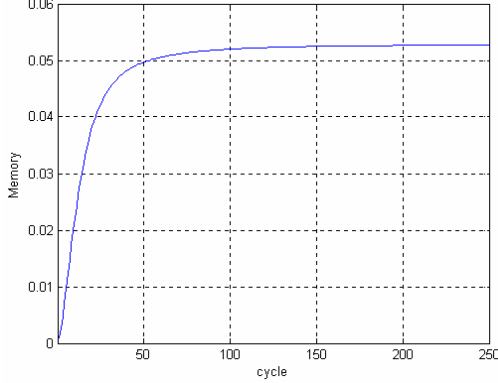
					
Figure 3.31.1 Sine approximation				Figure 3.31.2 Memory Convergence	
L	w	α	Training points	Maximum Error	Mean Error
27	27	0.1	(-180 : 15 : 180)	0.0639	0.0326
Required Memory Locations			Hash Size	Convergence	
387			No hashing	Constant	

Table 3.10 CMAC parameters and sine approximation results

In Table 3.11 the generalization width and the total number of layers are equal to 15387 memory locations are required without hashing. The learning rate is equal to 2 and remains constant during the learning. But as it is seen in Figure 3.32.1 the output performance of the CMAC approximation is very low. The high learning rate causes this situation. And the Figure 3.32.2 displays that the memory elements do not converge still after 2500 cycles. The output of the CMAC changes for every training cycle and never reaches to desired performance level.

In Table 3.12 the same CMAC parameters are used with the example in Table 3.11 but the learning rate is reduces from two to zero for every cycle. Finally after 50 cycles the memory converges and approximation is in the desired performance level.

It is seen that high learning rates cause instability. The memory contents of a CMAC with or without hash coding will converge, provided that the learning rate values lies between two and zero. Table 3.12 is an example for this case.

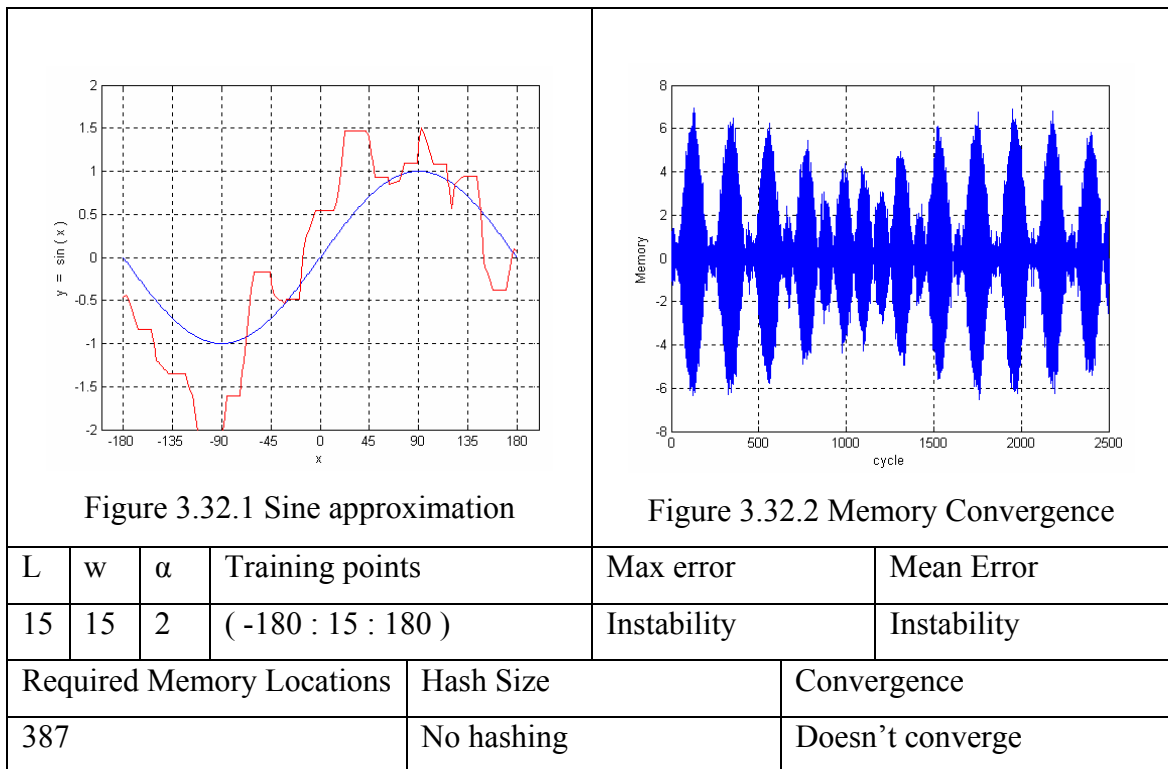


Table 3.11 CMAC parameters and sine approximation results

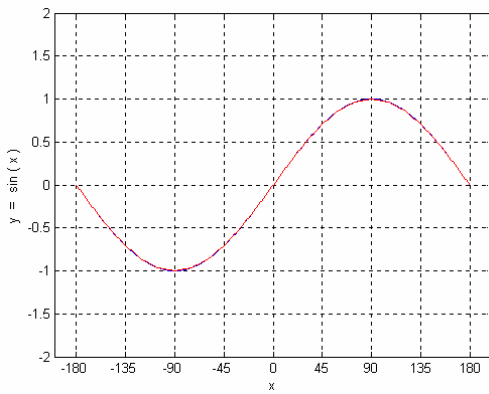


Figure 3.31.1 Sine approximation

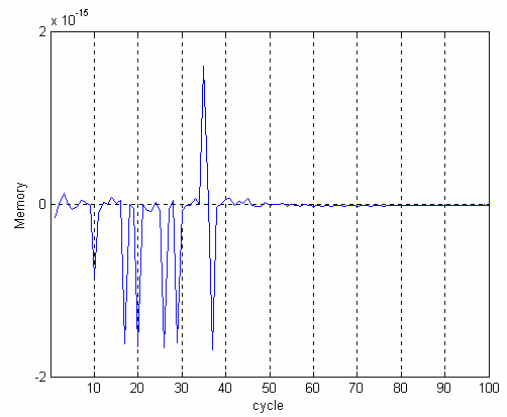


Figure 3.31.2 Memory Convergence

L	w	A	Training points	Maximum Error	Mean Error
15	15	$2 \rightarrow 0$	(-180 : 15 : 180)	0.0084	0.0036
Required Memory Locations			Hash Size	Convergence	
387			No hashing	Periodical	

Table 3.12 CMAC parameters and sine approximation results

CHAPTER 4

ROBOTIC CONTROL WITH CMACs

The artificial neural networks theory made it possible to develop adaptive solutions to complex control problems, such as inverse kinematics control for robotic systems. In this chapter a CMAC network is used for the inverse kinematics control of a two degrees of freedom serial manipulator. In the first section general concepts of the robotic control are outlined. The second section explains the inverse kinematics problem for the serial manipulators. The CMAC network and the control architectures are presented with the simulation results in the third section. A hardware implementation of two degrees of freedom serial manipulator is seen in the fourth section.

4.1. Robotic Control

The task of the robotic control is separated into two groups as motion control and force control. The motion control is a point to point control or continuous trajectory control. The control scheme can be open loop or closed loop. Very few robots use stepper motors or other actuators which can be controlled in an open fashion. Usually, manipulators are powered by actuators which output a torque or a force at each joint [20]. Figure 4.1 shows the basic idea of robotic control. Motion planning includes trajectory generation and forward/inverse kinematics computation. A robot is composed of joint motors, breaks, feedback sensors like position or velocity sensors or other special sensors such as force or torque sensors. Controller type is one of the most considerable factors of the robot control system. In present robot control systems, simple independent joint PID controllers are widely used. Actually, the control problem

of robotic manipulators is non-linear but the nonlinearities of the system are cancelled and the linear controllers are designed for the linear system. This is called the computed torque method.

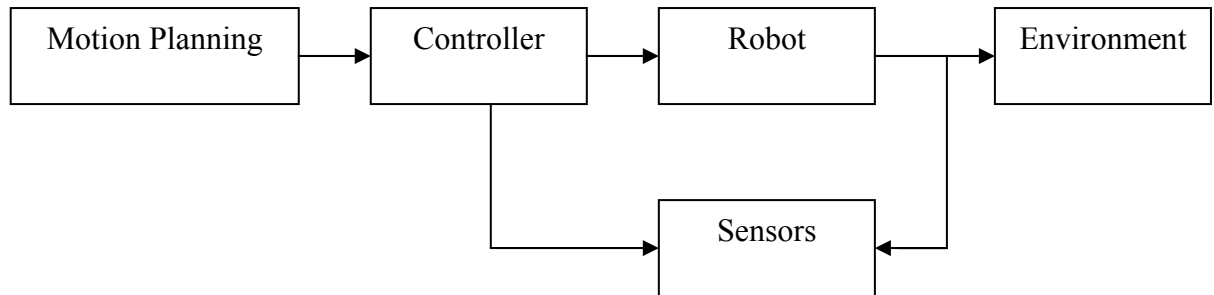


Figure 4.1 Basic Blocks of Robotic System

Each joint is considered independent, and the inertia reaction of each actuator is constant. For an n-DOF robot, the dynamics are described as:

$$D(q)\ddot{q} + C(q, \dot{q})\dot{q} + F(q, \dot{q}) + G(q) = \tau \quad (4.1)$$

where,

q : vector of joint variables,

τ : control torque vector,

$D(q)$: inertia matrix,

$C(q, \dot{q})$: coriolis and centrifugal force vector,

$G(q)$: gravitational force vector.

The dynamic control of such a robot system is seen in Figure 4.2. There are some disadvantages of computed torque method. The dynamic model is not known exactly. There are unmodelled dynamics such as friction, flexibility in the drive chain, noise, etc...

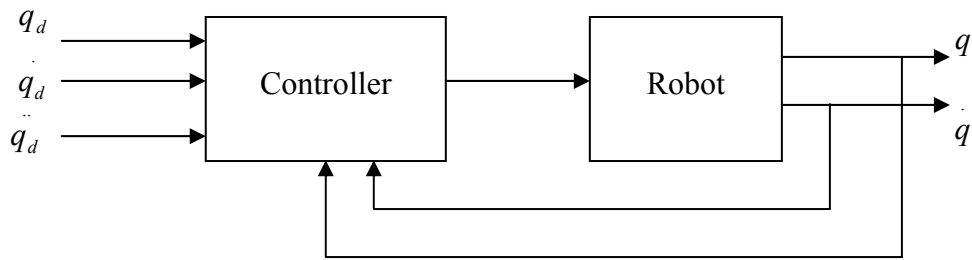


Figure 4.2 Functional block diagram of a dynamic robot control system

Real physical plants like robots often exhibit these non-linearity and variations due to the plant nature, noise or other factors. It is difficult to control such plants practically and precisely. Neuro controllers are good alternatives to conventional controllers. They have adaptation capabilities and also they can learn the real dynamics of the robot system. There are three basic tasks that the neuro controller can perform:

- (1) The neuro controller learns from a complex automatic controller.
- (2) Making a system or plant follow a desired set point or follow a reference model.
- (3) Optimization.

For a more general effective neural network control the plant's input-output to be controlled needs to be known [22].

In supervised learning, a set of training inputs $X(t)$ and targets $Y^*(t)$ for $t=1$ to t , is given to the network. The task is to learn how to generate $Y^*(t)$ for any given value of $X(t)$. In neurocontrol, $X(t)$ may be a set of sensor readings while the targets are a vector of desired control actions, $u^*(t)$ shown in Figure 4.3.

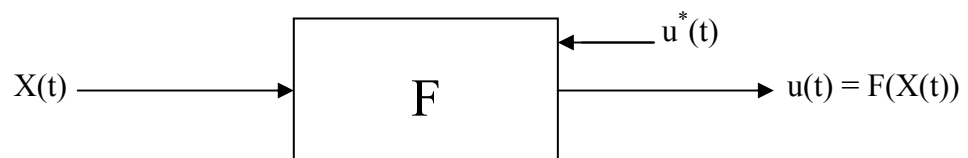


Figure 4.3 Neuro control in block

Neural networks based control systems may be open loop or closed loop. The open loop training is seen in Figure 4.4 where U_d is the actual input, and U refers to the output of the neural network approximation. The aim is to train the neural network so that U approximates U_d , the desired signal, as closely as possible. A closed loop training methodology with a controller can be used, shown in Figure 4.5. Here U_r is the persistent excitation that is added to the control input from the probing signal $U_d(t)$ to the system. With the controller and the persistent excitation input, the closed loop training methodology will ensure the collection of sufficiently rich training data. After training the neural networks can be used as a series type neuro controller shown in Figure 4.6. To consider the adaptive plant control scheme the neuro controller can be structured as in Figure 4.7.

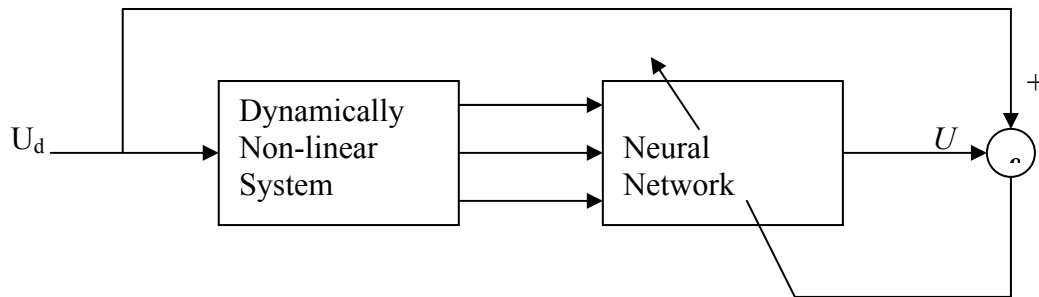


Figure 4.4 Open loop training scheme

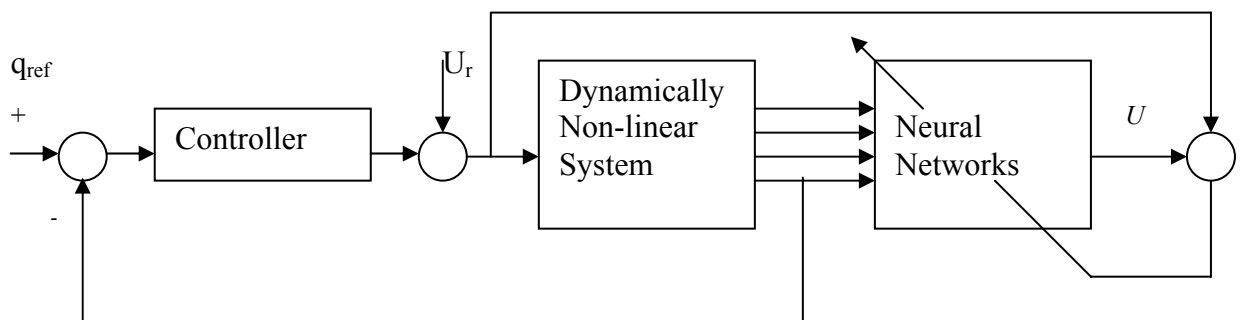


Figure 4.5 Closed loop training methodology

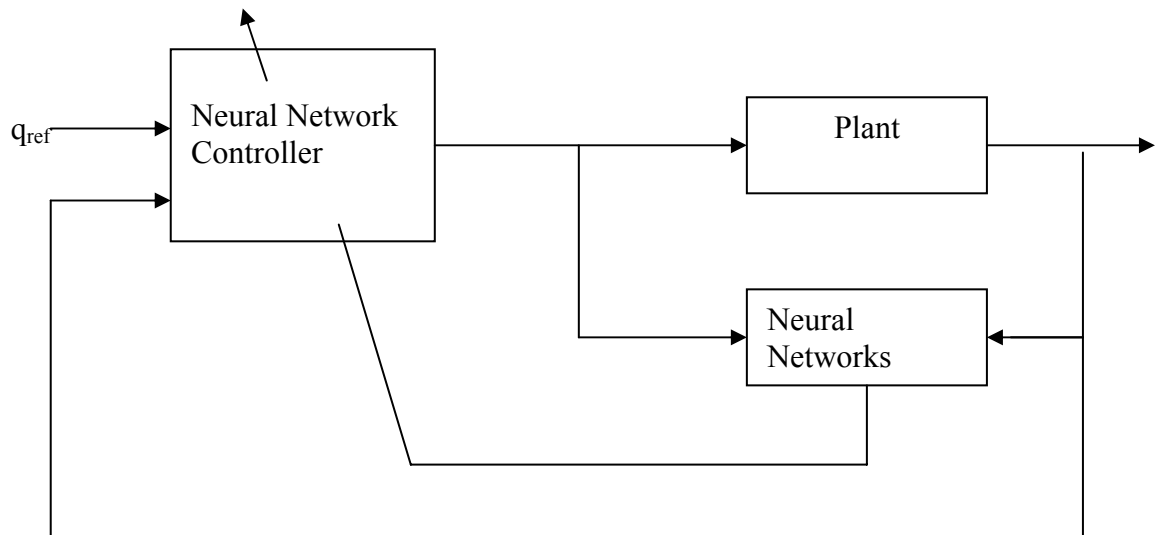


Figure 4.6 The structure of the adaptive plant control system based on neural networks

The neuro control approach as described in the literature can be classified into two categories:

- (i) Indirect neuro control approach
- (ii) Direct neuro control approach

In the indirect neuro control approach, the parameters of the plant are estimated at any instant and the parameters of the controller (weights) are adjusted assuming that the estimated parameters of the plant represent true values. However this approach requires a neural identifier and a neuro controller, thereby increasing the complexity of the control scheme. On the other hand, in direct neuro controller approach, no neural identifier for the plant is required. The neuro controller is connected in cascade with the plant. During the process of learning and adaptation the neural controllers learn about the behavior of the plant and adapts itself to achieve the desired control system performance [24].

The other perspective of robotic control is the inverse kinematics control problem of the robotic systems. It is a complex problem due to the non-linear equations. The desired position of the end point of the robot is specified in Cartesian Coordinates while the motions are actually obtained from the multiple actuators connected at the joints which decide the required joint angles. The transformation from Cartesian Coordinates to joint angles is a sophisticated problem especially in the case of many degrees of freedom.

4.2. Inverse kinematics for position

The problem of inverse kinematics is to find the joint angles, for a given end-effector position and orientation. In general, inverse kinematics is much harder than forward kinematics. Sometimes no analytical solution is possible, and an iterative search is required. Even with analytic solutions possible, multiple solutions arise from which one must pick. In the case of redundant manipulators, there may be many solutions. Another complication is that the workspace limits may be exceeded, the point may be outside the reach of the manipulator, or joint limits are exceeded. Geometric solution is one of the solutions for the inverse kinematics problem. In a geometric approach the geometry of the arm is decomposed into several plane geometry problems. Joint angles can be found by using the geometric formulas. The simplest manipulator to study inverse kinematics is the planar two degrees of freedom manipulator. Since the arm is planar, the plane geometry is applied to find a solution to the manipulator seen in Figure 4.7.

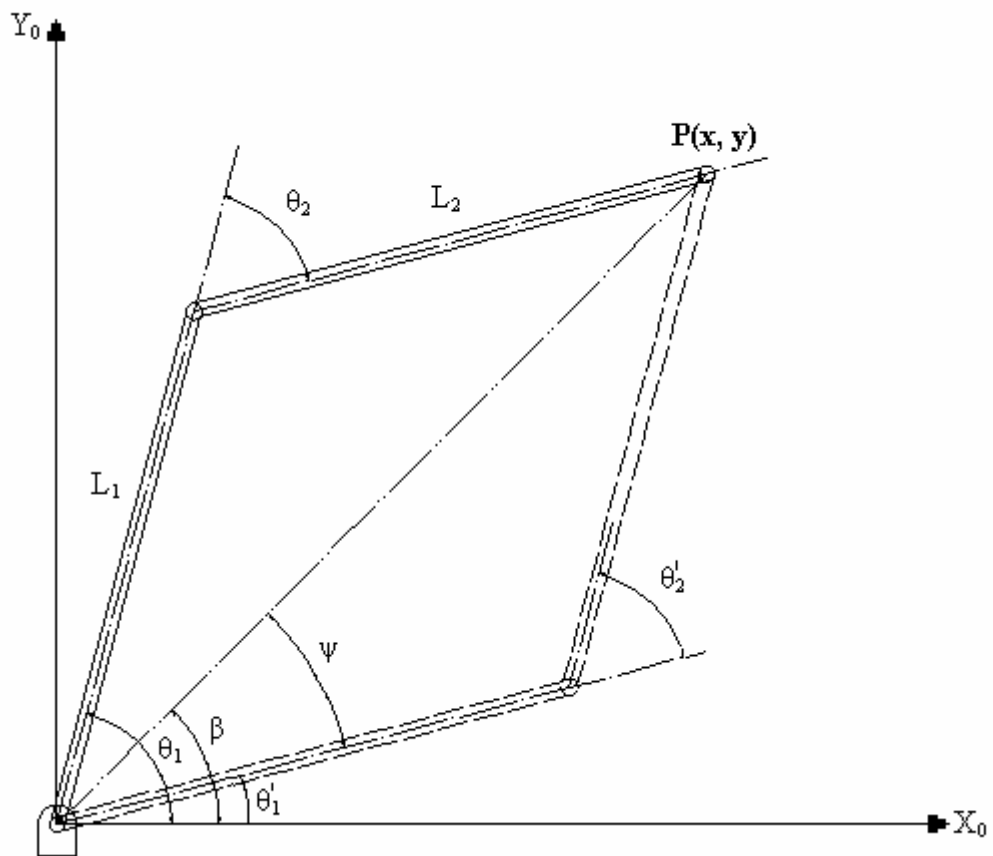


Figure 4.7 Plane geometry associated with a 2-link planar manipulator

To solve θ_2 law of cosines is applied:

$$x^2 + y^2 = L_1^2 + L_2^2 - 2L_1L_2 \cos(180 + \theta_2) \quad (4.2)$$

Since $\cos(180 + \theta_2) = -\cos(\theta_2)$, then

$$\cos(\theta_2) = \frac{x^2 + y^2 - L_1^2 - L_2^2}{2L_1L_2} \quad (4.3)$$

Equation 4.3 is solved for θ_2 between 0 and -180 degrees. The other solution is the symmetric position for $\theta'_2 = -\theta_2$. The expressions for the angles β and ψ are found.

The value of angle β depends on the sign of x and y so two argument arctangent is used:

$$\beta = A \tan 2(y, x) \quad (4.4)$$

The law of cosines is again applied to find ψ .

$$\cos(\psi) = \frac{x^2 + y^2 + L_1^2 - L_2^2}{2L_1\sqrt{x^2 + y^2}} \quad (4.5)$$

where $0 \leq \psi \leq 180$. Then:

$$\theta_1 = \beta \pm \psi \quad (4.6)$$

where the plus sign is used if $\theta_2 < 0$ and minus sign is used if $\theta_2 > 0$.

4.3. The inverse kinematic control with CMAC

The inverse kinematic control problem is shortly finding each individual joint angles as mentioned before. The angles are calculated by using the formulations 4.2, 4.3, 4.4, 4.5 and 4.6. Rather than using these formulations, CMAC is used here to evaluate the angles. The task is motion control (point to point in the defined workspace). The rate of the motion is constant. For the desired end-effector positions in the workspace (x, y coordinates of the end effector), the angles θ_1 and θ_2 are calculated. CMAC is trained in a supervised manner so, to find the training data set, the geometric equations can be used. The CMAC network of the two-link manipulator is composed of two CMACs. The coordinates of the desired end effector positions are the inputs to both CMACs and each CMAC outputs the individual joint angles. The CMAC network with two inputs for the inverse kinematics is displayed in Figure 4.8.

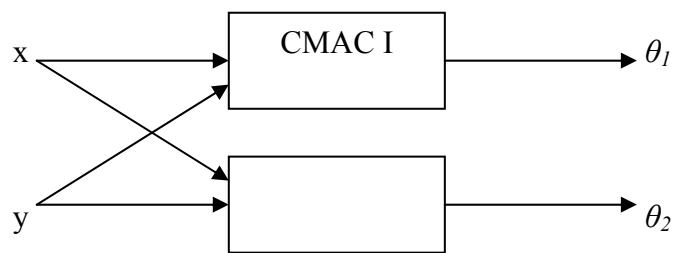


Figure 4.8 CMAC network for inverse kinematics of two-link manipulator

In the CMAC network architecture of the two-linked manipulator two CMACs are used. The network inputs are x, y coordinates and the outputs are θ_1 and θ_2 joint angles. Each output is related with both inputs. For estimating the θ_1 , x and y must be taken into account so the network is designed as shown in Figure 4.8. θ_1 and θ_2 are nonlinear because of the trigonometric functions and the squared terms. The problem becomes much more complex as the number of links increases. The standard methodology for calculating the inverse kinematics is training the neural network off-line for possible data to obtain solutions. Because of the generalization property, neural networks can learn the associated patterns and recall the learned patterns. The trained network is then used to achieve the desired movements. This technique therefore involves two steps of operation as training phase and performing phase. From another

point of view the advantage of using neural network for control problems is that neural networks have the ability of online learning and adaptive capabilities.

The inverse kinematics control scheme of the 2 DOF manipulator with CMAC is seen in Figure 4.9.

The desired x , y positions of the end effector are applied to the CMAC network. The network parameters of the CMAC are:

generalization width = 64

total number of layers = 64

learning rate = 0.5

Initially, all the weights are equal to zero. The output of the CMAC are the joint angles θ_1 and θ_2 which are inputs to the robot's forward kinematics. The error signals are calculated as the difference between the desired end-effector positions and the actual end-effector positions. It is shown that the two-linked robotic system with CMAC can reach any desired end-effector positions in the robot workspace. The desired x_d and y_d coordinates of the end effector are selected as:

$$x_d = [300 \ 100 \ 400], \quad y_d = [50 \ 250 \ 100].$$

The desired end effector positions are applied to CMAC network. The x and y positions of the end effector are shown in Figure 4.10 and the corresponding joint angle trajectories are shown in Figure 4.11.

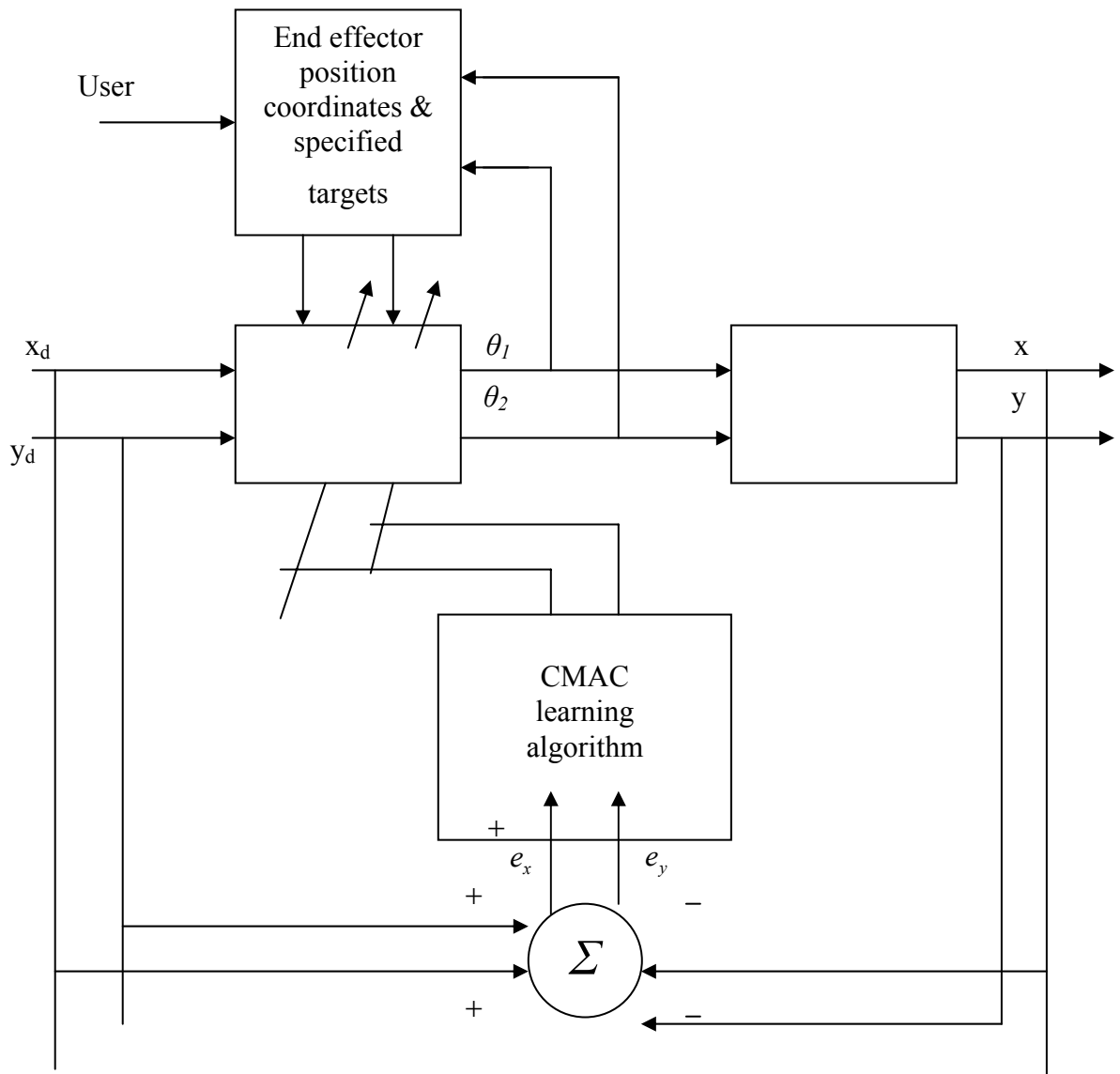


Figure 4.9 Block diagram for online learning of inverse kinematics of two-DOF manipulator

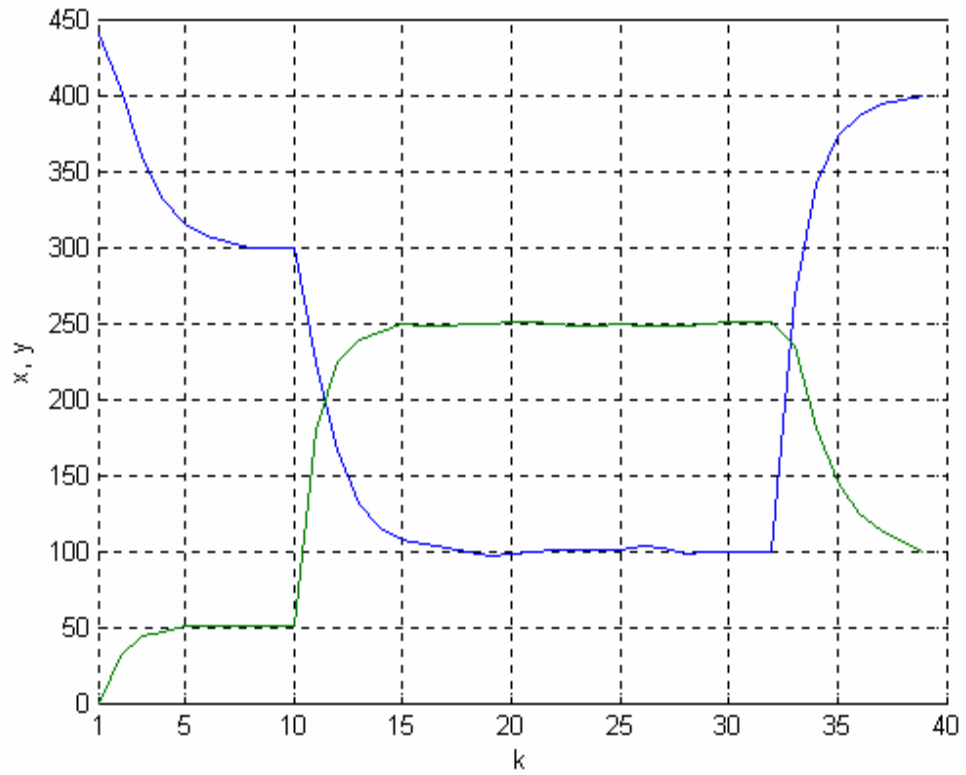


Figure 4.10 Simulation of the actual positions of the end effector of the two-linked robot

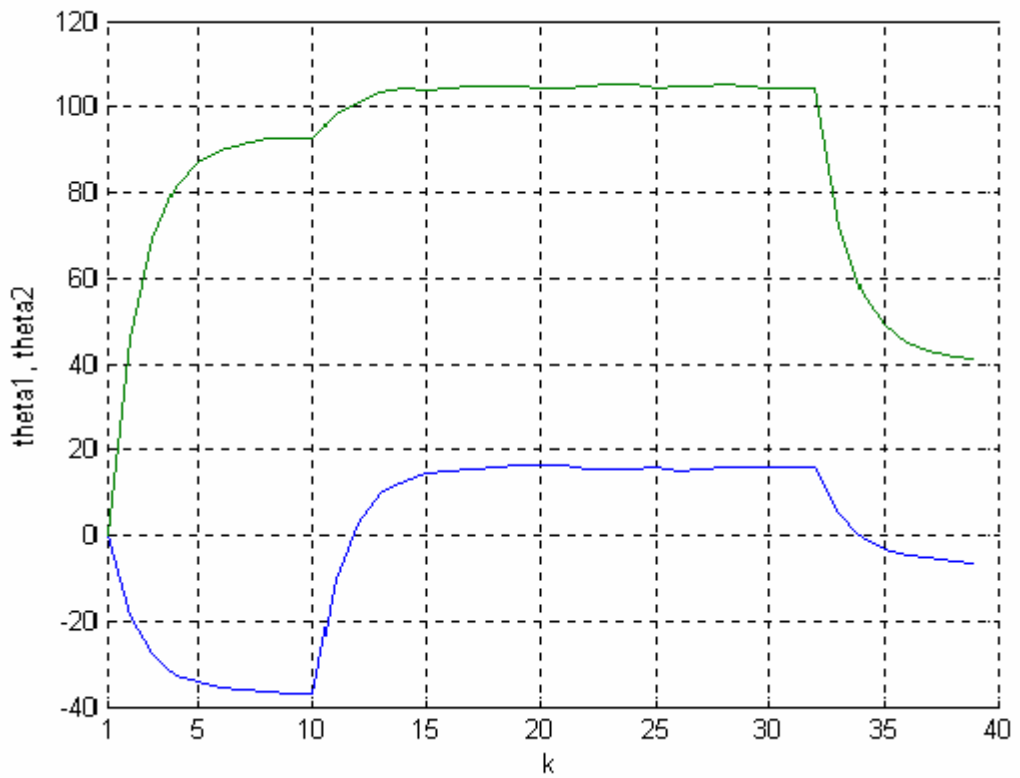


Figure 4.11 Joint angle trajectories of the two-linked robot

It is seen that 39 iterations are needed to reach the desired end-effector positions. The CMAC can be a fast solution for the inverse kinematics problem in robotics. On the other hand CMAC training is fast. Usually while it takes too much time for other network topologies CMAC is trained quickly. As a second case the two-link robot arm is trained offline and its performance figured out with graphics. The training data is selected in three different ways. First the training data is selected in a random fashion. The random training points are shown in Figure 4.12. Second the neighborhood sequential training technique is used. The neighbor training points are seen in Figure 4.13. Finally, the training points are selected in symmetry of the workspace's circle center as shown in Figure 4.14. The workspace is a semi-circle where the radius is equal to 440 mm. 165 points are trained in each technique.

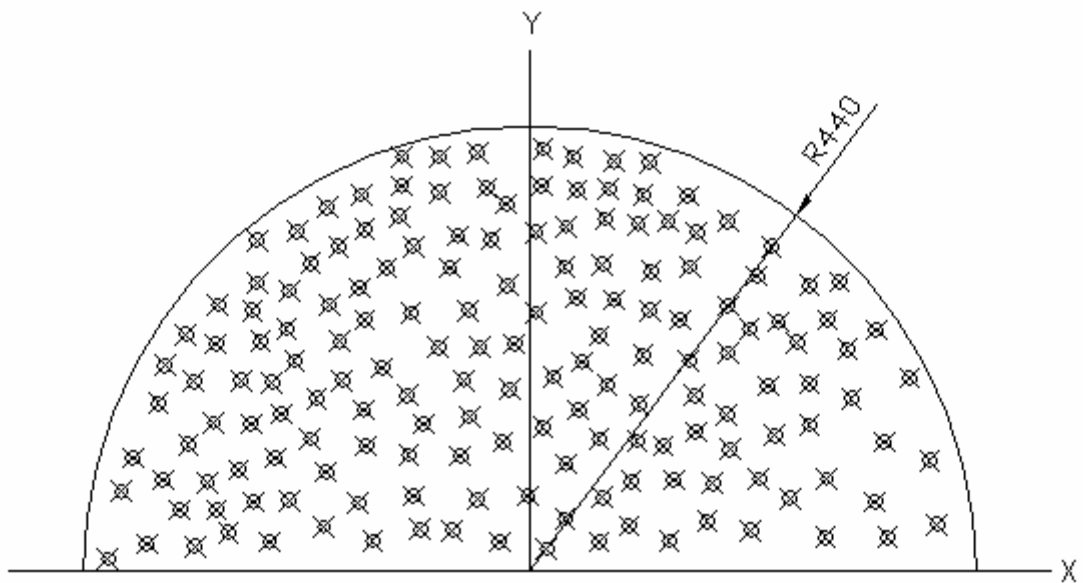


Figure 4.12 Random selected training data in the workspace of the two-linked robot arm

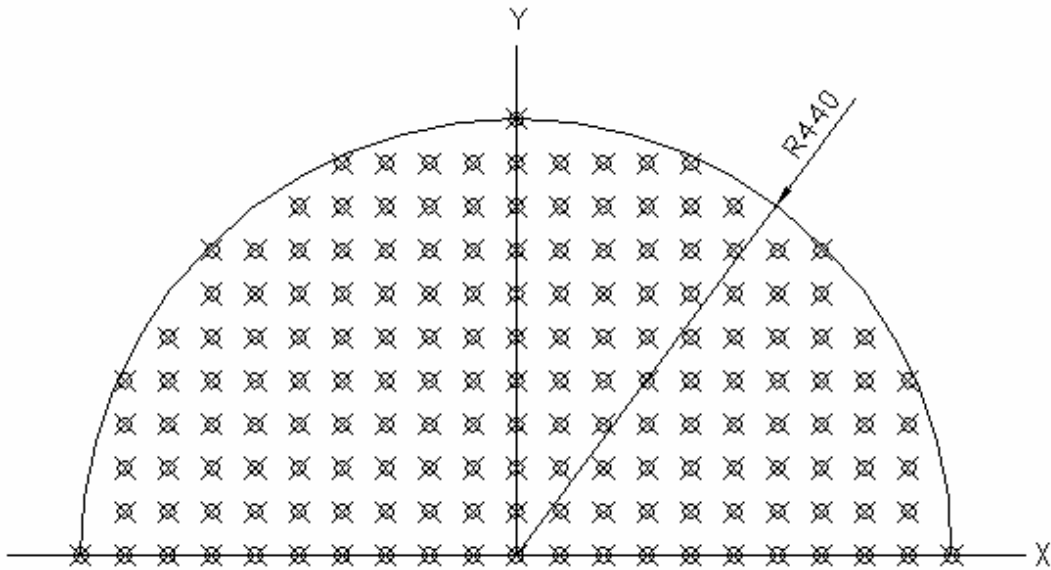


Figure 4.13 Sequence training data in the workspace of the two-linked robot arm

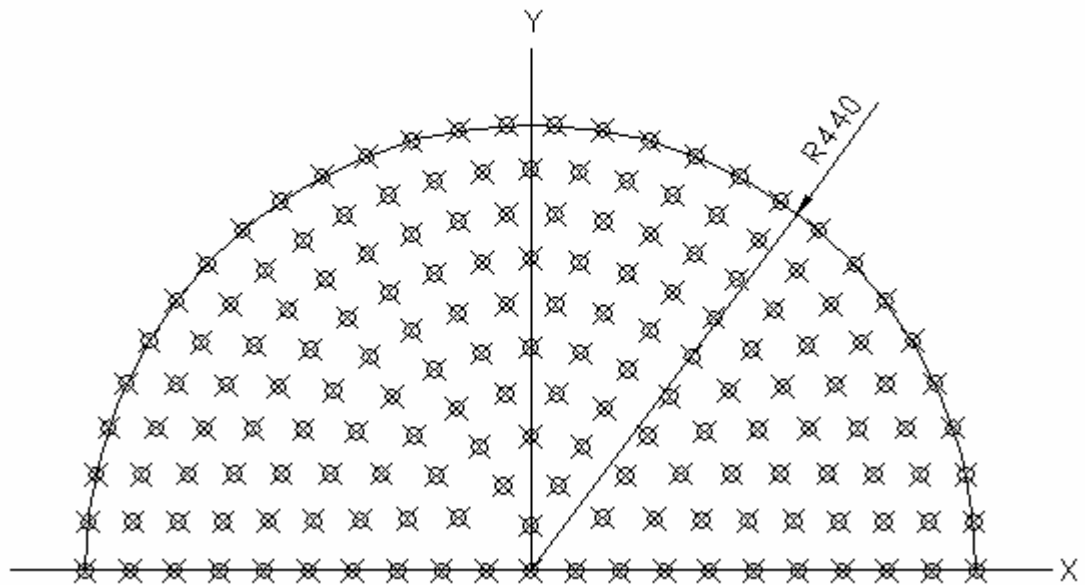


Figure 4.14 Polar symmetric training data in the workspace of the two-linked robot arm

Figure 4.15, Figure 4.16 and Figure 4.17 present the performance of each mentioned training schemes. In Figure 4.15 the random training performance is seen. Generalization width and total number of layers are equal to 164. Memory converges after 10 cycles. In Figure 4.16 neighborhood sequential training method's performance is seen where the generalization width and the total number of layers are 44 and finally in Figure 4.17 the output errors of the network whose training data set is selected as in Figure 4.14 are seen. Here the generalization width and total number of layer are equal to 96. The desired end-effector positions are as follows:

```

xd = [-331 -198 -239 -109 201 243 330 300 200 44 0 100 -300 440 2 120 -1 -200 -50
-300 354 20 375 -5 -440];
yd = [ 111 64 285 242 290 149 67 200 300 44 380 250 2 3 60 200 300 10
5 50 17 98 150 0];

```

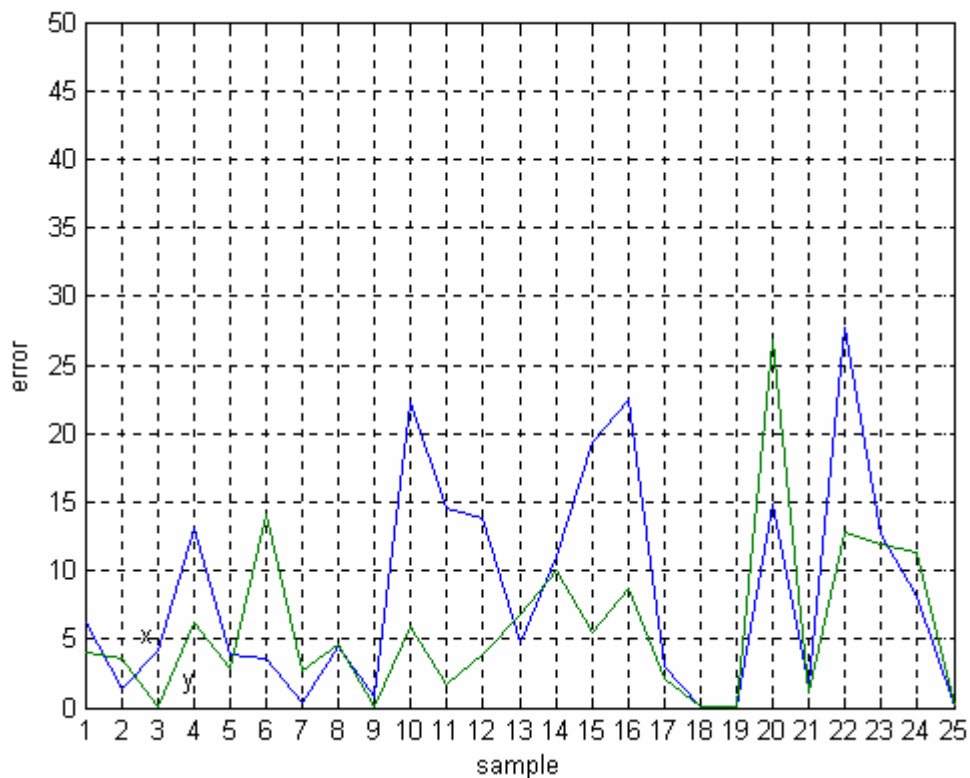


Figure 4.15 The output error for the random trained network

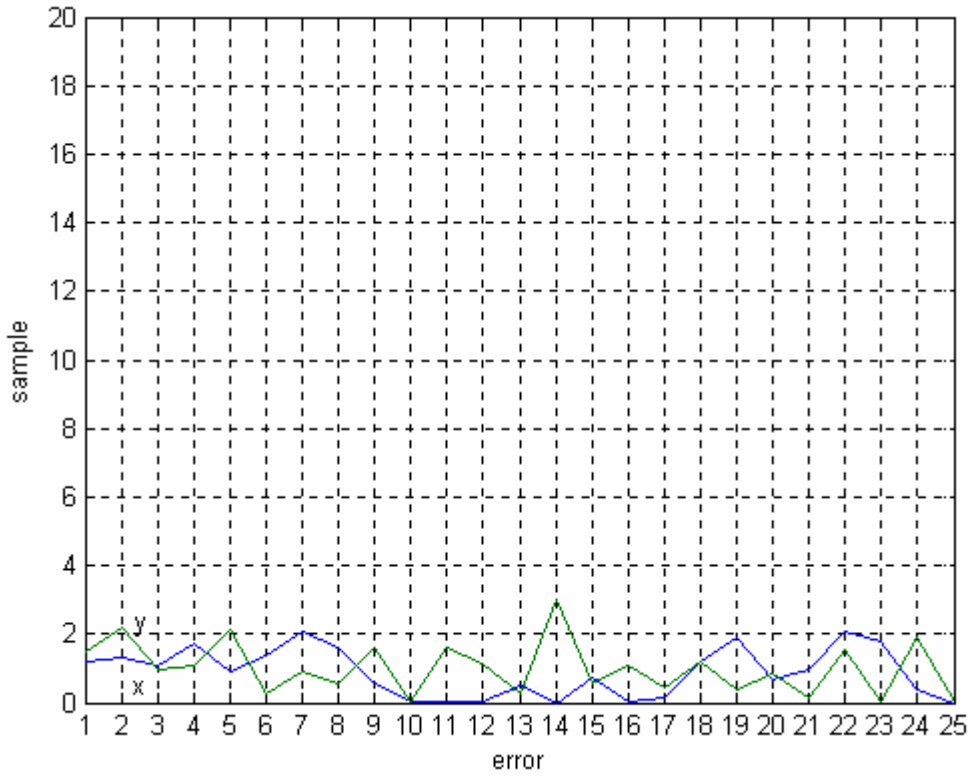


Figure 4.16 The output error for the sequentially trained network

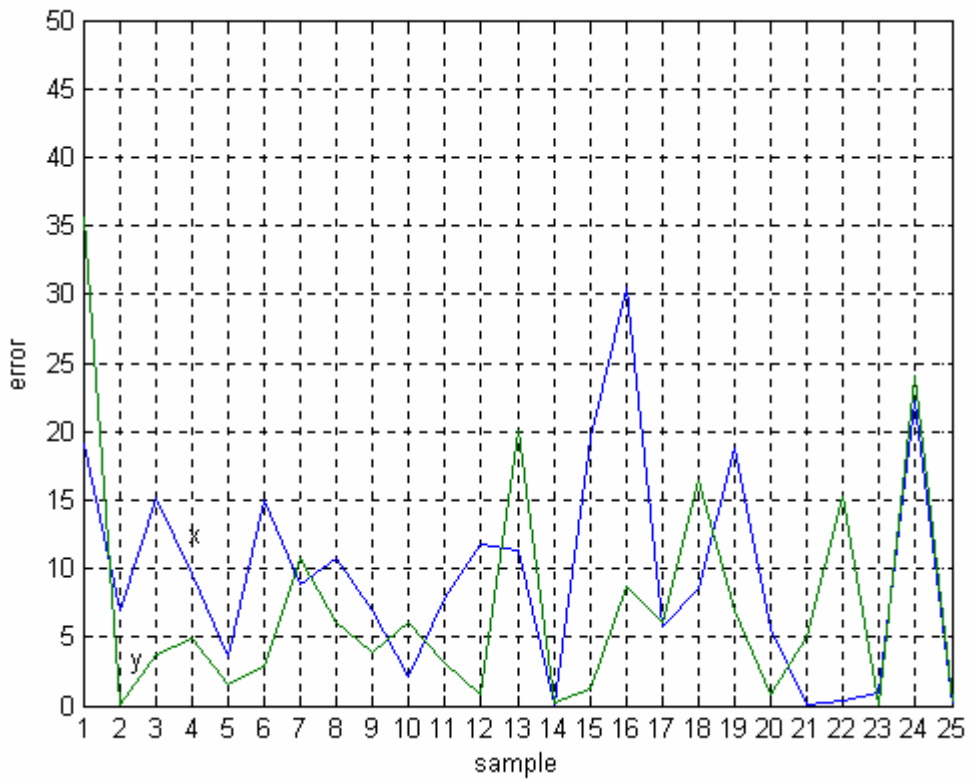


Figure 4.17 The output error for the symmetric trained network

It is seen that sequentially trained network performance is higher than the other two methods. Also it is a fast training method because the memory converges at first cycle.

4.4. The hardware implementation of a two- DOF manipulator

The manipulator realized physically in this study is a two degrees of freedom robotic arm. Step motors are used as the joint actuators. The electronic circuit connected to the PC parallel port drives each step motors. The control scheme is open loop. CMAC is used for the inverse kinematics calculations. The training is performed in an off-line fashion. The task of the robot is moving to the coordinates that are specified by the user. In this section stepper motors are defined. Also the driver circuit of the steppers and the physical view of the robotic arm are displayed.

4.4.1. Step Motors

Step motors are the electrical motors that are driven by digital pulses rather than applying a continuous voltage. Each pulse equals one rotary step which is a portion of one complete rotation. Counting pulses can be applied to achieve a desired shaft rotation of the motor. The count automatically represents how much movement has been achieved, without feedback information like in the servo systems. So open loop control is appropriate for this concept. Accuracy of the step motor is a result of the mechanical precision of its parts and assembly and some other noises. But this error can be negligible. The more steps cause greater precision. And also some step drivers divide normal steps into half steps or micro steps.

A step motor converts digital pulse inputs to shaft rotation. The rotation speed is related to the frequency of the pulses. Between steps, the motor holds its position and its load without any brake system in its mechanism. After the motion the stepper holds its load when it stops. Mechanical motion, load and the speed are the criteria for selecting a step motor.

Variable reluctance, permanent magnet and hybrid are the basic types of the step motors. They generally operate with step angles from 5 degrees to 15 degrees at high step rates, and have no detent torque. Detent torque is the holding torque when no current is flowing in the motor. In Figure 4.18, when phase A is energized, rotor teeth line up with the stator teeth of phase A by magnetic attraction. The next step is taken

when A is turned off and phase B is energized. Continuing the sequence, C is turned on and next and then A again. Reverse rotation is achieved when the phase order is reversed. Permanent motors differ from variable reluctance motors by having permanent magnet rotors with no teeth, and are magnetized perpendicular to the axis. In energizing the four phases in sequence, the rotor rotates as it is attracted to the magnetic poles. The motor shown in Figure 4.18 will take 90 degree steps as the windings are energized in sequence A, B, C and D. Permanent magnet motors generally have steps 45 or 90 degrees and step at relatively low rates, but they exhibit high torque and good damping characteristics.

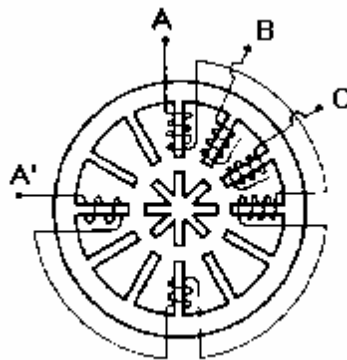


Figure 4.18 Variable Reluctance Motor

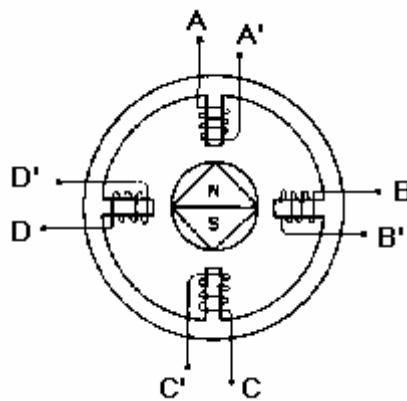


Figure 4.19 Permanent Magnet Motor

Hybrid types of step motors seen in Figure 4.20 combine the qualities of the variable reluctance motors and permanent magnet motor. They have high detent torque and excellent holding and dynamic torque, and they can operate at high speeds. Normally, they exhibit step angles of 0.9 to 5 degrees. If the phases energized one at a

time, the rotor rotates in full step. This motor can also be driven two phases at a time to yield more torque, or one then two then one phase, to produce half steps.

The computer or programmable logic controller (PLC) sends commands to the driver. The drivers determine amount, speed and rotation direction. They accept pulses and direction signals and translate these signals into phase currents in the motor. A step motor driver provides precisely speed and positioning. The motor increments a precise step with each control pulse easily converting digital information to exact incremental rotation without the need for feedback devices such as tachometers or encoders. Because the system is open loop, the problems due to the feedback loop and instability are eliminated.

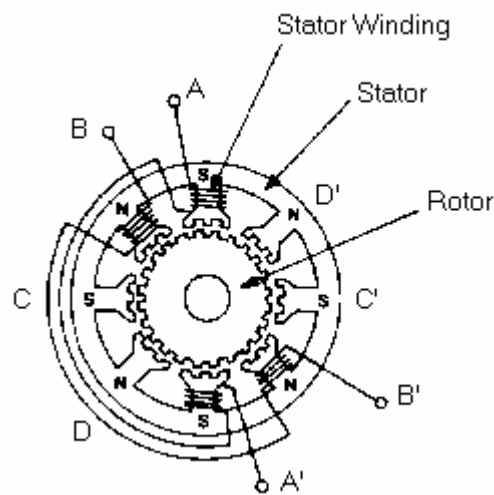


Figure 4.20 Hybrid motor

4.1.2. Step Motor Driver Circuit

NPN type transistors are used for the driver design seen in the circuit in Figure 4.21.

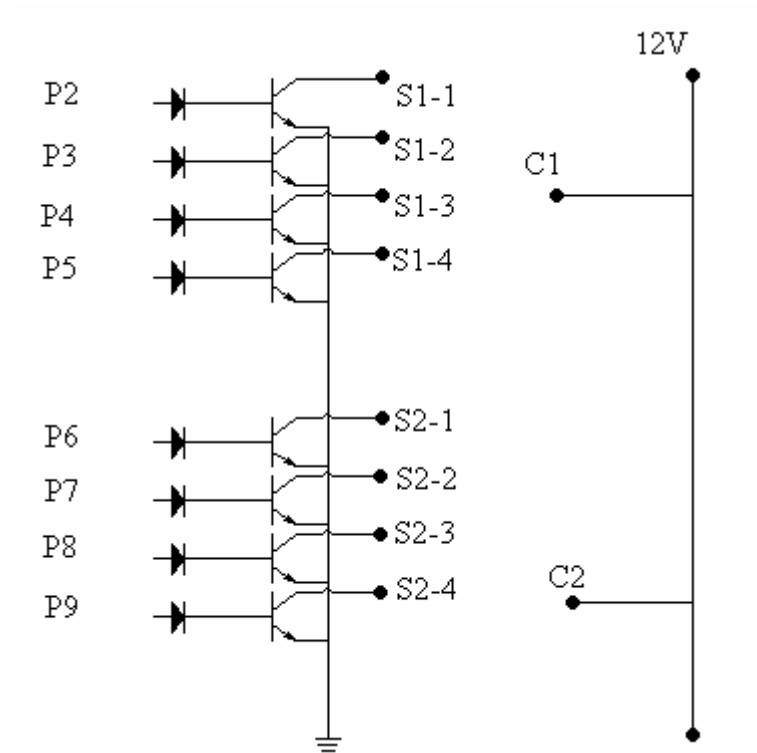


Figure 4.21 Step motor driver circuit

Two step motors are driven in one driver circuit. P2, P3, ... , P9 are the output pins of the parallel port. S1-1, ... , S1-4 are the phase connections of the first stepper likewise S2-1, ... , S2-4 are the phase connections of the second step motor. C1 and C2 are the common phases of the first and the second stepper.

4.1.3. Experimental setup description

The hardware architecture block diagram of the real control system considered here is shown in Figure 4.22. The picture of the setup including the control system is shown in Figure 4.23. The experimental setup consists of a two-linked robot arm with its actuators, and the driver circuits.

The arm is designed as a plane redundant manipulator where each joints can travel among 360 degrees. Two steppers drive the mechanism. The rotation of the step

motor is reduced with a gear. This gear rotates the shaft that is connected with the link. The link lengths are 220 mm (distance between two rotating shafts' axis).

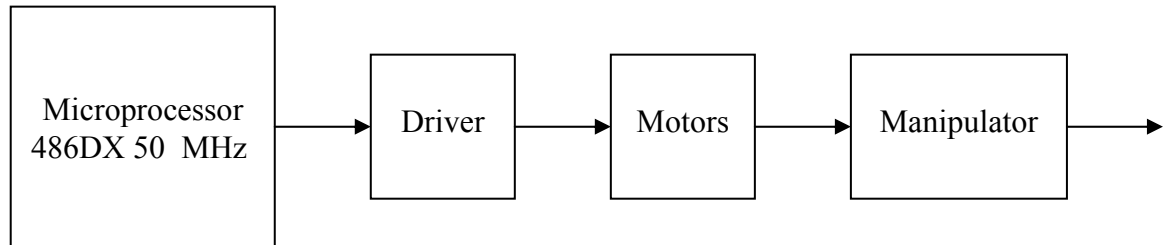


Figure 4.22 Block diagram of the control system

The advantages of the mechanism are that it is controlled without feedback. Each step motor is hybrid type and rotates 7.5 degrees for full step. The step motors are driven with half steps so each pulse causes 3.75 degrees rotation. The rotation is reduced to 13 / 42 for the first step motor and 16 / 42 for the second step motor. The resolution is about 1.1607 degrees per pulse for the first step motor and 1.4285 for the second step motor. The motors are fed with +12 DC voltage. The control algorithm is implemented on a 486 DX-50 MHz personal computer using MATLAB programming language. The drawing of the robot arm is displayed in Figure 4.23 and the parts of the arm are listed in Table 4.1.

1	First Gear Box' Lower Plate	8	Bolt M3
2	First Gear Box' Upper Plate	9	Second shaft
3	Bolt M4	10	Second link (220 mm)
4	First shaft	11	First Gear Box' driver gear
5	First link (220 mm)	12	First Gear Box' shaft gear
6	Second Gear Box' Lower Plate	13	Second Gear Box' driver gear
7	Second Gear Box' Upper Plate	14	Second Gear Box' shaft gear

Table 4.1 Robot arm parts

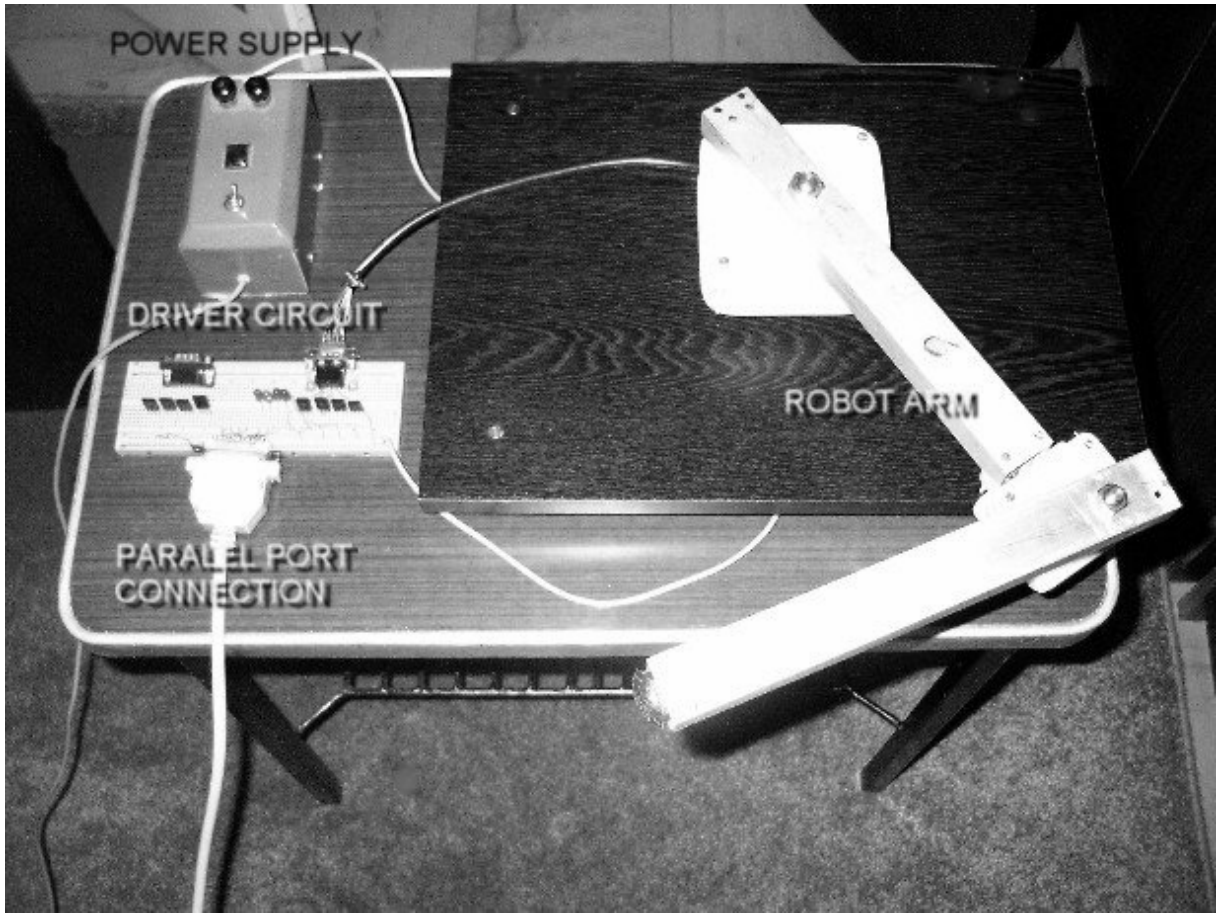


Figure 4.23 Experimental hardware setup

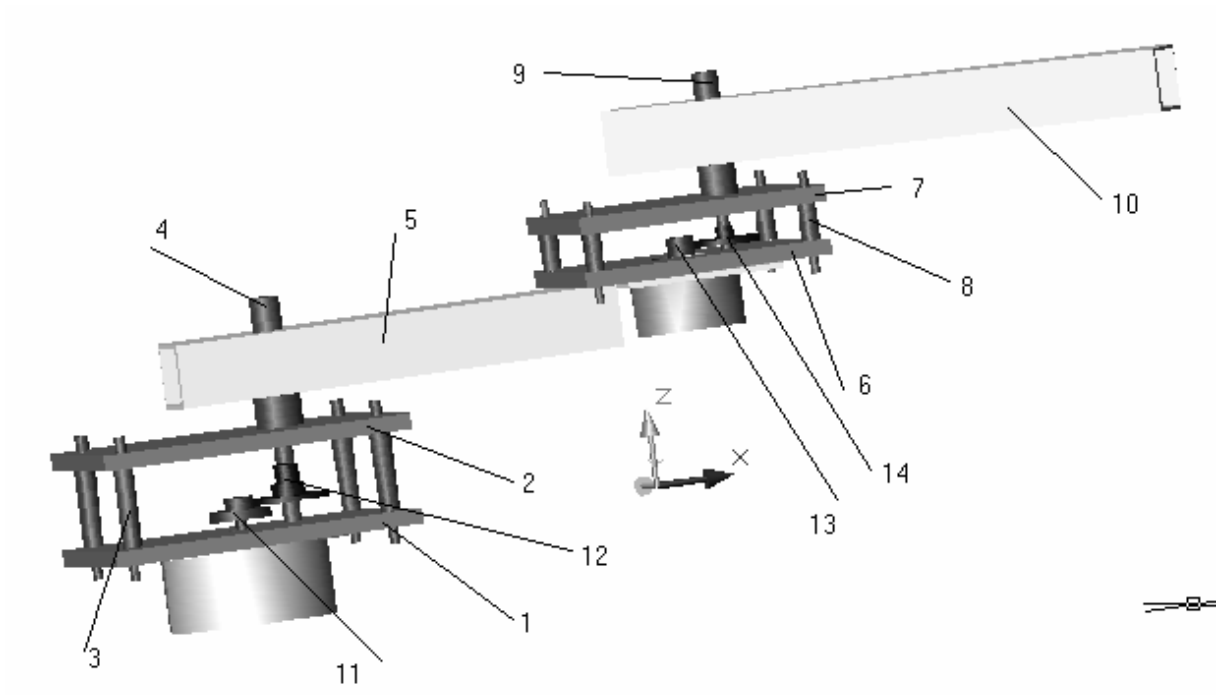


Figure 4.24 Robot arm drawing

CHAPTER 5

CONCLUSIONS

In this thesis, CMAC neural networks are studied. The CMAC operation is defined with examples. The network parameters and their effects on the system performance were analyzed in detail. Aim of the thesis is generating a two degrees of freedom manipulator's inverse kinematics by using CMACs.

The learning techniques are divided into two groups as sequential neighborhood training and random training. It is seen that sequential neighborhood training is a fast and efficient method for the problem of inverse kinematics. The optimum results are obtained when generalization width is equal to total number of layers. And if the distance between two training points is equal to the generalization width the CMAC approximates a smooth curve. Also the other advantage of sequential neighborhood training is the less memory requirements. By using hash coding the required memory decreases dramatically. As a result for inverse kinematics calculations, a sequentially neighborhood trained CMAC network's performance is a good alternative. The main advantage of CMAC to other neural networks is its fast computation. In this study only a two degrees of freedom manipulator is discussed but in the case of many degrees of freedom, the analytic solutions are more complicated and sometimes there are no formulations for the inverse kinematics. In such situations some iteration methods take place. But these solutions are very slow computations according to CMAC computation.

The thesis gives an idea for designing a CMAC network. Many engineering problems are non-linear and in real life problems to propose an accurate mathematical model is not possible for all situations.

During the analysis of CMAC network and hardware implementation, MATLAB programming language is used on a PC. The simple nature of CMAC operation is an advantage for the application areas.

The main disadvantage of CMAC is the large memory requirement. Hash coding is a solution for the memory problem but it causes hash collisions. Furthermore specific hashing algorithms for CMAC may overcome memory problems.

Stability is another subject for CMAC. Some adaptive algorithms are developed for stability problems of CMAC [9]. These adaptive algorithms need to be researched. CMAC has strong approximation ability and it has a fast computation. It is suitable for intelligence applications.

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APPENDIX

MATLAB CMAC CODE SAMPLES

```
% #####
% CMAC 1 INPUT ~ 1 OUTPUT FUNCTION APPROXIMATION
% #####
% -----
% initialization
% -----
    layer_num = 55;
    min_ip_val = -180;
    max_ip_val = 180;
        w = 55; % generalization width
        lr = 1; % learning rate
        ip_val = max_ip_val - min_ip_val + 1;
% -----
% total memory location calculation
% -----
    sayi=0;
    for i = 1 : layer_num;
        sayi = sayi + ceil( (ip_val - mod((i-1),w)) /w )+ sign(i-1)*1;
    end
        twn = sayi; % total memory location number
% -----
% input & target values
% -----
    xx = -180:180;
    rx = randperm(361);
    trp_num = 43;
    ix = rx(1:trp_num);
```

```

        x = xx(ix(:));

for i = 1 : trp_num;
    t(i) = sin(x(i)*pi/180); % target matrix
end
% -----
% CMAC memory parameters
% -----
hash_size = 200; % hash_size = twm for no hashing
Mem = zeros(1,hash_size);
% -----
% training
% -----
for sayac = 1 : 250;
for j = 1 : trp_num;
% map hypercube address
    for i = 1 : layer_num
        s(i) = ceil( (ip_val - mod((i-1),w)) /w )+ sign(i-1)*1;
        ddizin = min_ip_val+(mod((i-1),w)) : w : max_ip_val;
        if ddizin(1) == min_ip_val
            dizin = ddizin;
        else
            dizin = [min_ip_val ddizin];
        end
% hypercube no in that layer
        hypcube(i) = max(find(dizin<=x(j)));
% hypercube index no
        if i == 1;
            hyp_no(i) = hypcube(i);
            if hyp_no(i) > hash_size
                hyp_no(i) = mod(hyp_no(i), hash_size);
                if hyp_no(i) == 0;
                    hyp_no(i) = 1;
                end
            end
        end
    end
end
end
end

```

```

        end
    else
        hyp_no(i) = sum(s(1:(i-1))) + hycube(i);
        if hyp_no(i) > hash_size
            hyp_no(i) = mod(hyp_no(i), hash_size);
            if hyp_no(i) == 0;
                hyp_no(i) = 1;
            end
        end
    end
end

end

OP(j) = sum(Mem(hyp_no(:)));
Mem(hyp_no(:)) = Mem(hyp_no(:)) + lr * (t(j) - OP(j)) / layer_num;
end

convergence(sayac) = sum(Mem);
end

% -----
% OUTPUT
% -----

for s_x = min_ip_val:max_ip_val;
    for i = 1 : layer_num
        s(i) = ceil( (ip_val - mod((i-1),w)) /w )+ sign(i-1)*1;
        ddizin = min_ip_val+(mod((i-1),w)) : w : max_ip_val;
        if ddizin(1) == min_ip_val
            dizin = ddizin;
        else
            dizin = [min_ip_val ddizin];
        end
    end

    % hypercube no in that layer
        hycube(i) = max(find(dizin<=s_x));

    % hypercube index no
    % hypercube index no
        if i == 1;
            hyp_no(i) = hycube(i);

```

```

        if hyp_no(i) > hash_size
            hyp_no(i) = mod(hyp_no(i), hash_size);
            if hyp_no(i) == 0;
                hyp_no(i) = 1;
            end
        end
    end
else
    hyp_no(i) = sum(s(1:(i-1))) + hypcube(i);
    if hyp_no(i) > hash_size
        hyp_no(i) = mod(hyp_no(i), hash_size);
        if hyp_no(i) == 0;
            hyp_no(i) = 1;
        end
    end
end
end

    end

OUTPUT(s_x+abs(min_ip_val)+1) = sum(Mem(hyp_no(:)));
end

% -----
% PLOT
% -----

m = min_ip_val : max_ip_val;
n = sin( m * pi / 180 );

plot(m,n,'b', m,OUTPUT,'r' )
grid on
dif = n-OUTPUT;
%figure (2)
%plot(ind,dif,'g')
max_error = max(abs(dif))
mean_error = sum(abs(dif))/ip_val
% -----
% #####

```



```

% #####
% CMAC 2 INPUT ~ 1 OUTPUT FUNCTION APPROXIMATION
% #####
% -----
% initialization
% -----
    layer_num = 15;
    min_ip_val = 1;
    max_ip_val = 181;
        w = 15; % generalization width
        lr = 1; % learning rate
        ip_val = max_ip_val - min_ip_val + 1;
% -----
% total memory location calculation
% -----
    sayi = 0;
    ssayi = 0;
    for i = 1 : layer_num;
        sayi = ceil( (ip_val - mod((i-1),w)) /w )+ sign(i-1)*1;
        ssayi = ssayi + sayi^2;
    end
    twm = ssayi; % total memory location number
% -----
% input & target values
% -----
    trp_num_ = 12; % training point number in one axis
        xx = min_ip_val : ((max_ip_val - min_ip_val)/(trp_num_)) : max_ip_val;
        lexx = length(xx);
        x = repmat(xx, 1, lexx); % x-component
    for i = 1 : lexx
        yy = repmat( xx(i), 1, lexx );
        y( ((i-1)*lexx+1) : (i*lexx) ) = yy;
    end

```

```

    trp_num = length(x);
    for i = 1 : trp_num;
        t(i) = sin(x(i)*pi/180) * cos(y(i)*pi/180);
    end

% -----
% CMAC memory parameters
% -----

hash_size = twm; % hash_size = twm for no hashing
Mem = zeros(1,hash_size);
% -----
% training
% -----

for sayac = 1 : 250;
    for j = 1 : trp_num;
% map hypercube address
        for i = 1 : layer_num
            s(i) = ceil( (ip_val - mod((i-1),w)) /w ) + sign(i-1)*1;
            ss(i) = s(i)^2;
            ddizin = min_ip_val+(mod((i-1),w)) : w : max_ip_val;
            if ddizin(1) == min_ip_val
                dizin = ddizin;
            else
                dizin = [min_ip_val ddizin];
            end
% hypercube no in that layer
            hypcube_x(i) = max(find(dizin<=x(j))); % x component
            hypcube_y(i) = max(find(dizin<=y(j))); % y component
% hypercube index no
            if i == 1;
                hyp_no(i) = s(i) * ( hypcube_x(i)-1 ) + hypcube_y(i);
                if hyp_no(i) > hash_size
                    hyp_no(i) = mod(hyp_no(i), hash_size);
                end
                if hyp_no(i) == 0;

```

```

        hyp_no(i) = 1;
    end
else
hyp_no(i) = sum(ss(1:(i-1))) + s(i) * ( hypcube_x(i)-1 ) + hypcube_y(i);

    if hyp_no(i) > hash_size
        hyp_no(i) = mod(hyp_no(i), hash_size);
    end
    if hyp_no(i) == 0;
        hyp_no(i) = 1;
    end
end
end
end
OP(j) = sum(Mem(hyp_no(:)));
Mem(hyp_no(:)) = Mem(hyp_no(:)) + lr * (t(j) - OP(j)) / layer_num;
end
convergence(sayac) = sum(Mem);
sayac
end
% -----
% OUTPUT
% -----
for s_x = min_ip_val : max_ip_val;
    for s_y = min_ip_val : max_ip_val;
        for i = 1 : layer_num
            s(i) = ceil( (ip_val - mod((i-1),w)) /w )+ sign(i-1)*1;
            ss(i) = s(i)^2;
            ddizin = min_ip_val+(mod((i-1),w)) : w : max_ip_val;
            if ddizin(1) == min_ip_val
                dizin = ddizin;
            else
                dizin = [min_ip_val ddizin];
            end
        end
    end
end
% hypercube no in that layer

```

```

    hypcube_x(i) = max(find(dizin<=s_x)); % x component
    hypcube_y(i) = max(find(dizin<=s_y)); % y component
% hypercube index no
    if i == 1;
    hyp_no(i) = s(i) * ( hypcube_x(i)-1 ) + hypcube_y(i);
        if hyp_no(i) > hash_size
            hyp_no(i) = mod(hyp_no(i), hash_size);
        end
        if hyp_no(i) == 0;
            hyp_no(i) = 1;
        end
    else
    hyp_no(i) = sum(ss(1:(i-1))) + s(i) * ( hypcube_x(i)-1 ) + hypcube_y(i);

        if hyp_no(i) > hash_size
            hyp_no(i) = mod(hyp_no(i), hash_size);
        end
        if hyp_no(i) == 0;
            hyp_no(i) = 1;
        end
    end
end
%OUTPUT((s_x+abs(min_ip_val)+1), (s_y+abs(min_ip_val)+1)) =
sum(Mem(hyp_no(:)));
OUTPUT(s_x,s_y) = sum(Mem(hyp_no(:)));
end
end
for n = 1 : 181
    for m = 1 : 181
        z(n,m) = sin(n*pi/180)*cos(m*pi/180);
    end
end
D = z - OUTPUT;

```

```

% #####
% CONTROL OF 2 DOF MANIPULATOR BY CMAC
% #####
% -----
% system parameters
% -----
    l1 = 220;
    l2 = 220;
    r = l1 + l2;
    layer = 44;
    min_ip = -(l1+l2);
    max_ip = (l1+l2);
    width = 44; % generalization width
    lr = 1; % learning rate
    ip = max_ip - min_ip + 1;
    tnow = memreq(layer,width,ip);
hash_size = tnow; % hash_size = twn for no hashing
    Mem1 = zeros(1,hash_size);
    Mem2 = zeros(1,hash_size);
% -----
% Input & target pairs
% -----
xt = [-440    -396    -352    -308    -264    -220    -176    -132    -88    -44
      0      44      88     132     176     220     264     308     352     396
      440 ...
     -396    -352    -308    -264    -220    -176    -132    -88    -44     0
      44      88     132     176     220     264     308     352     396 ...
     -396    -352    -308    -264    -220    -176    -132    -88    -44     0
      44      88     132     176     220     264     308     352     396 ...
     -396    -352    -308    -264    -220    -176    -132    -88    -44     0
      44      88     132     176     220     264     308     352     396 ...

```

```

-352  -308  -264  -220  -176  -132  -88  -44  0  44
  88   132  176  220  264  308  352 ...
-308  -264  -220  -176  -132  -88  -44  0  44  88
  132  176  220  264  308 ...
-308  -264  -220  -176  -132  -88  -44  0  44  88
  132  176  220  264  308 ...
-220  -176  -132  -88  -44  0  44  88  132  176
  220 ...
-176  -132  -88  -44  0  44  88  132  176 ...
440 ];

```

```

yt = [ 00  0  0  0  0  0  0  0  0  0
      0  0  0  0  0  0  0  0  0  0 ...
      44  44  44  44  44  44  44  44  44  44
      44  44  44  44  44  44  44  44  44 ...
      88  88  88  88  88  88  88  88  88  88
      88  88  88  88  88  88  88  88  88 ...
      132  132  132  132  132  132  132  132  132  132
      132  132  132  132  132  132  132  132  132 ...
      176  176  176  176  176  176  176  176  176  176
      176  176  176  176  176  176  176  176  176 ...
      220  220  220  220  220  220  220  220  220  220
      220  220  220  220  220  220  220 ...
      264  264  264  264  264  264  264  264  264  264
      264  264  264  264  264 ...
      308  308  308  308  308  308  308  308  308  308
      308  308  308  308  308 ...
      352  352  352  352  352  352  352  352  352  352
      352 ...
      396  396  396  396  396  396  396  396  396 ...
      0 ];

```

```

for i = 1 : length(xt);
if xt(i) == 0 & yt(i) == 0

```

```

theta1_d(i) = 0;
theta2_d(i) = 0;
else

    theta = ikt(xt(i), yt(i), l1, l2);
theta1_d(i) = theta(1);
theta2_d(i) = theta(2);

end

end

% -----
% start
% -----
for k = 1 : 1;

for j = 1 : length(xt)

    adres = hypno( layer,width,min_ip,max_ip,hash_size,xt(j),yt(j) );

    OP1 = sum(Mem1(adres(:)));
    Mem1(adres(:)) = Mem1(adres(:)) + lr * (theta1_d(j) - OP1) / layer;

    OP2 = sum(Mem2(adres(:)));
    Mem2(adres(:)) = Mem2(adres(:)) + lr * (theta2_d(j) - OP2) / layer;

c(k) = sum(Mem1);

end

end

xd = [-331 -198 -239 -109 201 243 330];

```

```
yd = [111 64 285 242 290 149 67];
```

```
for i = 1 : length(xd)
```

```
    adres = hypno( layer,width,min_ip,max_ip,hash_size,xd(i),yd(i));
```

```
    t1a(i) = sum(Mem1(adres(:)));
```

```
    t2a(i) = sum(Mem2(adres(:)));
```

```
    xa(i) = dkx( t1a(i), t2a(i), l1, l2 );
```

```
    ya(i) = dky( t1a(i), t2a(i), l1, l2 );
```

```
    err_x(i) = xd(i) - xa(i);
```

```
    err_y(i) = yd(i) - ya(i);
```

```
end
```


Matlab Functions

```
% inverse kinematics
% INPUTS : x : end-effector's x coordinate
%          y : end-effector's y coordinate
% OUTPUTS : THETA(1) : first joint angle
%          THETA(2) : second joint angle
```

```
function THETA = ikt( x,y,l1,l2);
```

```
theta2 = acos( (x^2 + y^2 - l1^2 - l2^2) / (2 * l1 * l2)) * 180 / pi;
    beta = atan2(y, x) * 180 / pi;
    ci = acos( (x^2 + y^2 + l1^2 - l2^2) / ( 2 * l1 * sqrt(x^2 + y^2) ) ) * 180 /
pi;
    if theta2 < 0
        theta1 = beta + ci;
    else
        theta1 = beta - ci;
    end
```

```
THETA(1) = theta1;
```

```
THETA(2) = theta2;
```

```
% forward kinematics
% INPUTS : theta1 : first joint angle
%          theta2 : second joint angle
% OUTPUTS : x : x coordinate of the end-effector
```

```
function x = dkx(theta1, theta2, l1, l2);
```

```
x = l1 * cos ( theta1 * pi / 180 ) + l2 * cos ( (theta1 + theta2) * pi / 180 );
```

```

% INPUTS : theta1 : first joint angle
%          theta2 : second joint angle
% OUTPUTS : y : y coordinate of the end-effector

function y = dky(theta1, theta2, l1, l2);

y = l1 * sin ( theta1 * pi / 180 ) + l2 * sin ( (theta1 + theta2) * pi / 180 );

% hypercube index finder

% INPUTS : layer_num : total number of layers
%          w : generalization width
%          min_ip_val : minimum input value
%          max_ip_val : maximum input value
%          hash_size : total number of hashed memory locations
%          x_a : x component of the input
%          y_a : y component of the input
% OUTPUT : h : hypercubes index no

% OUTPUTS : x : x coordinate of the end-effector

function h = hypno( layer_num, w, min_ip_val, max_ip_val, hash_size, x_a,
y_a)

ip_val = max_ip_val - min_ip_val + 1;
for i = 1 : layer_num
    s(i) = ceil( (ip_val - mod((i-1),w)) /w )+ sign(i-1)*1;
    ss(i) = s(i)^2;
    ddizin = min_ip_val+(mod((i-1),w)) : w : max_ip_val;
    if ddizin(1) == min_ip_val
        dizin = ddizin;
    else
        dizin = [min_ip_val ddizin];

```

```

        end
    % hypercube no in that layer
        hypcube_x(i) = max(find(dizin<=x_a)); % x component
        hypcube_y(i) = max(find(dizin<=y_a)); % y component
    % hypercube index no
        if i == 1;
            hyp_no(i) = s(i) * ( hypcube_x(i)-1 ) + hypcube_y(i);
            if hyp_no(i) > hash_size
                hyp_no(i) = mod(hyp_no(i), hash_size);
            end
            if hyp_no(i) == 0;
                hyp_no(i) = 1;
            end
        else
            hyp_no(i) = sum(ss(1:(i-1))) + s(i) * ( hypcube_x(i)-1 ) + hypcube_y(i);

            if hyp_no(i) > hash_size
                hyp_no(i) = mod(hyp_no(i), hash_size);
            end
            if hyp_no(i) == 0;
                hyp_no(i) = 1;
            end
        end
    end
end
h = hyp_no;

```

```

% step motor driver
% half step per each pulse
% INPUTS : loop : rotation loop
%           t : pulse period
%           direction : rotation direction (cw, ccw)
% OUTPUT : angle1 : angle traveled after command
% parallel port's 2nd-3rd-4th-5th pins are used.
function angle1 = semistep1(loop, t, direction) % valid for matlab version 6.5

dio=digitalio('parallel','lpt1');
Port0=addline(dio,0:7,0,'out'); %Pin 2-9

if direction == 1;
for k = 1 : loop;
putvalue(Port0,8);
pause(t);
putvalue(Port0,12);
pause(t);
putvalue(Port0,4);
pause(t);
putvalue(Port0,6);
pause(t);
putvalue(Port0,2);
pause(t);
putvalue(Port0,3);
pause(t);
putvalue(Port0,1);
pause(t);
putvalue(Port0,9);
pause(t);
end
else
for k = 1 : loop;
putvalue(Port0,9);

```

```
pause(t);
putvalue(Port0,1);
pause(t);
putvalue(Port0,3);
pause(t);
putvalue(Port0,2);
pause(t);
putvalue(Port0,6);
pause(t);
putvalue(Port0,4);
pause(t);
putvalue(Port0,12);
pause(t);
putvalue(Port0,8);
pause(t);
end
end
```