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Palestine Polytechnic University

College of Engineering and Technology

Mechanical Engineering Department

Mechatronics Engineering

Graduation Project

Self Powered Solar Tracking System

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According to the project supervisor and according to the agreement of the testing committee members, this project is submitted to the Department of Mechanical Engineering at college of engineering and technology in partial fulfillment of the requirements of the bachelor's degree.

Department Head Signature

Name: ________________

Supervisor Signature

Name: Tariq Abuhamdia

June-2009

Dedication

To our families, to our teachers, to our friends, to our university and to everybody supported us We dedicate this work

We dedicate this project

Project team

Title

Self Powered Solar Tracking System

Acknowledgment

Here as we finished our project we stop for a moment to thank every body who has helped us to complete this work.

First we want to thank our supervisor Eng. Tariq Abuhamdieh who gave us a lot of time and experience in order to complete the project and gave us the opportunity to start scientific life and methodology in the real life by asking us to do this work.

Special thanks related to university teachers in mechanical engineering department, who gave us valuable notes on our project and used to encourage us to complete the project in full way.

Abstract

Self Powered Solar Tracking System

By

Ahmad Al.Bakri **Hasan Al.Muhtaseb**

The main idea of this project is to control a gyroscopic system that tracks the solar radiation during the day to maximize the output power from the solar panel which is expected to increase by 20-30% over the power of a fixed panel [8]. The tracking is done by using smaller photo cells to detect the light variation, this variation is the error signal used by the controller to drive the motors to the right position again.

PIC microcontroller is used to control the whole system with a PI controller, solar panel will charge a battery such that it is used to provide the actuators with the power needed for the motion, in addition an over charge controller will control the charging process.

Table of Contents

List of figures

Chapter One

Introduction

1.1 Introduction

1.2 System description

1.3 Literature Review

1.4 Principle of Operation

1.5 Importance of the project

1.6 Connections between the Project and Benefited Parties

1.7 Project Schedule

1.8 Project Budget

1.9 Text Content

1.1 Introduction

This project aims to control the motion of a solar module such that it can track the sun path in order to increase its output power through the day by 20% to 30% over the regular stand still solar systems; this process is done by controlling actuators by microcontroller such that the panel faces sun rays all the time.

Sun tracking needs using solar sensors that will detect the variation in sun's position and then comparing the change in their output power, the controller then can drive the actuators to move the panel to the exact position.

In the following chapters the solar system description along with the other mechanical and electrical components used will be shown and explained in details.

It is hoped that at the end of this thesis the reader can get good and clear idea about the project basics and purposes.

1.2 System Description

1.2.1 Block Diagram

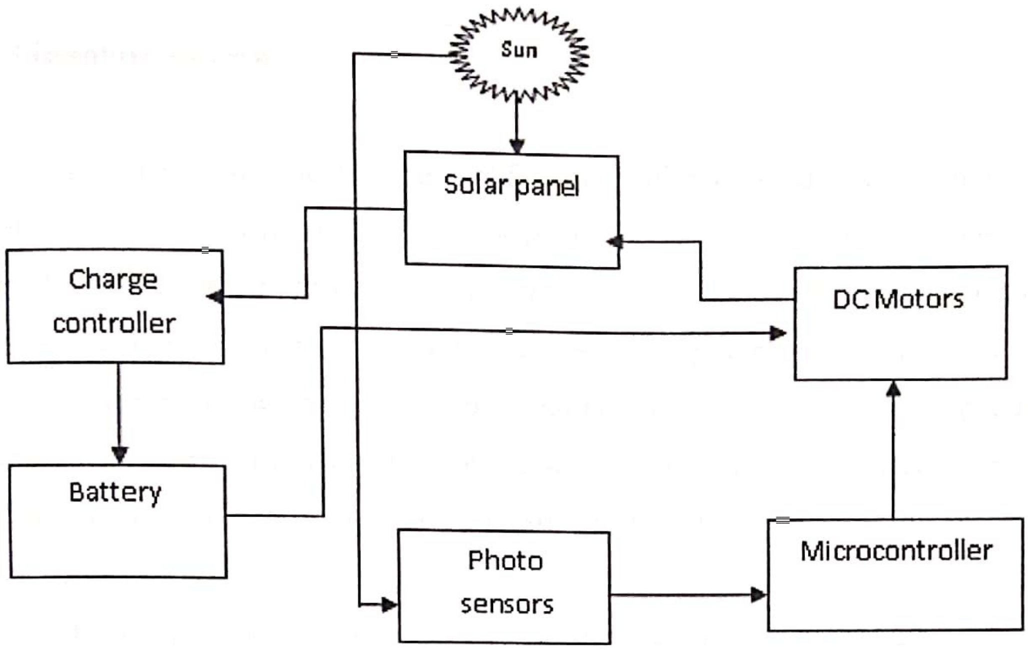


Fig 1.1 General block diagram

1.2.2 Principle of operation:

Sun provides the solar energy for the panel, which in turn charges the battery through an over charge controller, As the path of the sun changes with time photo sensors provide the microcontroller with the amount of change that must be performed in the position of the panel such that it faces the sun again.

Then the Microcontroller gives the signal to the actuators to rotate the panel around two axes till it reaches the position where it gains the maximum power and that will be detected by the sensors.

Since the system is self- powered tracker its motors will get the power they need from its own battery thus there is no need for any external power source.

1.3 Literature Review

The need to increase the efficiency of the solar panels has given the motive to the researchers to develop these panels and their orientation, this started in 1983 as in this research *"Sun tracking by peak power positioning for photovoltaic concentrator arrays"* a microcomputer-based solar tracking and control system (TACS) capable of maintaining the peak power position of a photovoltaic array by adjusting the load on the array for maximum efficiency and changing the position of the array relative to the sun.

Then the idea was developed by using microprocessors as in this research *"versatile microprocessor based controller for solar tracking"* a microprocessor-based solar tracking controller was designed and fabricated, In addition to tracking, the controller is capable of acquiring photovoltaic and metrological data from a photovoltaic system and controlling battery / load.

Then their was some attention to the maximum power tracking point without using concentrators as in *"Investigating the effectiveness of maximum power point tracking for solar system"* this paper investigates the effectiveness of maximum power point tracking; using a vector methodology to track the direction and path of the sun throughout the day, the optimal solar tracking angle and angle of incidence of the sun's rays are derived.

Another research is based on the use of fuzzy control based on PC which used 2 DC motors to track the solar sun rays to increase the efficiency, the most relevant research to the discussed project here is *"versatile microprocessor* *based controller for solar tracking"* but here the system is using a microcontroller instead of using microprocessor.

1.4 Project Goals

The goals of this project are to apply the principles of Mechatronics engineering, to get the maximum power of a solar panel by tracking sunlight in addition to increasing the reliability of renewable energy for the promising future it has.

1.5 Importance of the Project

The importance of the project is to increase the efficiency of solar energy systems in order to get the maximum possible power, and so increasing the reliability of using solar modules in various applications.

1.6 Connections between the Project and Benefited Parties

One of the major sectors that this project serve is the energy sector where factories and other facilities can use such system for reducing energy consumption by using efficient PV system for lighting and other applications, besides in Rural areas where buildings or houses are at a considerable distance from the public electricity supply (or grid) self powered solar tracker presents an efficient solution and perfect energy source, for various mobile systems this project solves the problems of static panels that need to be adjusted to constant azimuth and inclination angles.

1.6 Project Schedule

Table 1.1: Project time-schedule for first semester

Process	Week														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Choosing group	■														
Project determination		■													
Conceptual design			■	■											
Literature review				■	■	■	■								
Motion analysis						■	■	■	■	■					
Mechanical design								■	■	■	■	■			
Electrical design											■	■	■	■	
Control design												■	■	■	■
Writing documentation								■	■	■	■	■	■	■	■

Table 1.2: Project time-schedule for second semester

Process	Week														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
modifying design	■	■	■	■											
Mechanical implementation					■	■	■	■							
Electrical implementation							■	■	■	■	■	■			
Microcontroller implementation								■	■	■	■	■	■	■	■
Microcontroller programming											■	■	■	■	■
Testing project								■	■	■	■	■	■	■	■
Writing documentation					■	■	■	■	■	■	■	■	■	■	■

1.8 Project Budget

Table 1.3: Project Budget

component	number	price(NIS)
solar panel	1	1300
DC motor	2	200
charge controller	1	200
Battery	1	460
mechanical structure	_	1500
microcontroller	1	100
electronic wiring	_	100
Solar system importing fees	_	800
total		**4660**

Chapter 2

Solar energy and PV basics and principles

2.1 Solar energy:

The sun has produced energy for billions of years. Solar energy is the sun's rays (solar radiation) that reach the earth.

Solar energy can be converted to thermal (or heat) energy and used to heat water for use in homes, buildings or swimming pools and to heat spaces inside greenhouses, homes and other buildings.

Solar energy can be converted to electricity by either using PV devices such as watches and calculators or using solar power to heat fluids which will produce steam that can be used to power the generators in power plants facilities.

2.2 Photovoltaic energy

"Photovoltaic energy is the conversion of sunlight into electricity. A photovoltaic cell, commonly called a solar cell or PV, is the technology used to convert solar energy directly into electrical power. A photovoltaic cell is a non-mechanical device usually made from silicon alloys". [5]

the principle of operation of the PV cell is that when light strikes a PV cell with a certain wavelength some photons are absorbed by the cell while the others are reflected, the absorbed ones can provide energy to energize the electrons at the surface of the cell which in response leave their locations making holes with positive charge while the electrons are grouped together causing a p-n junction which creates a potential voltage difference like the battery's cathode and anode.

"When the two surfaces of the p-n layers are connected through an external load, electricity flows. The photovoltaic cell is the basic building block of a photovoltaic system. Individual cells can vary in size from about 1 centimeter (1/2 inch) to about 10 centimeter (4 inches) across. However, one cell only produces 1 or 2 watts, which isn't enough power for most applications. To increase power output, cells are electrically connected into a packaged weather-tight module. Modules can be further connected to form an array. The term array refers to the entire generating plant, whether it is made up of one or several thousand modules. The number of modules connected together in an array depends on the amount of power output needed". [5]

Of course the climate conditions affects the performance of the PV cells like fog or cloudy weather, Photovoltaic cells like batteries, generate direct current (DC) which is generally used for small loads (electronic equipment). When DC current from photovoltaic cells is used for commercial applications or sent to electric utilities using the electric grid, it must be converted to alternating current (AC) using inverters.

Historically, PV has been used at remote sites to provide electricity. In the future PV arrays may be located at sites that are also connected to the electric grid enhancing the reliability of the distribution system.

2.3 PV Module orientation

"Photovoltaic (PV) modules work by converting sunshine directly into electricity. Sunlight is the essential ingredient. PV modules work best when their cells are perpendicular to the Sun's incoming rays. Adjustment of static mounted PV modules can result in from 10% to 40% more power output yearly.

The problem is that the Sun constantly moves in relation to the stationary PV module. Actually, the apparent motion of the Sun is due to the Earth's motion, even if a module is placed so that it is perpendicular to the Sun at solar noon; it is not even close to perpendicular in the morning and evening. This daily east to west solar motion is called solar azimuth. Also consider that the Sun's apparent height in the sky changes from winter to summer. This yearly north to south solar motion is called solar declination." [4]

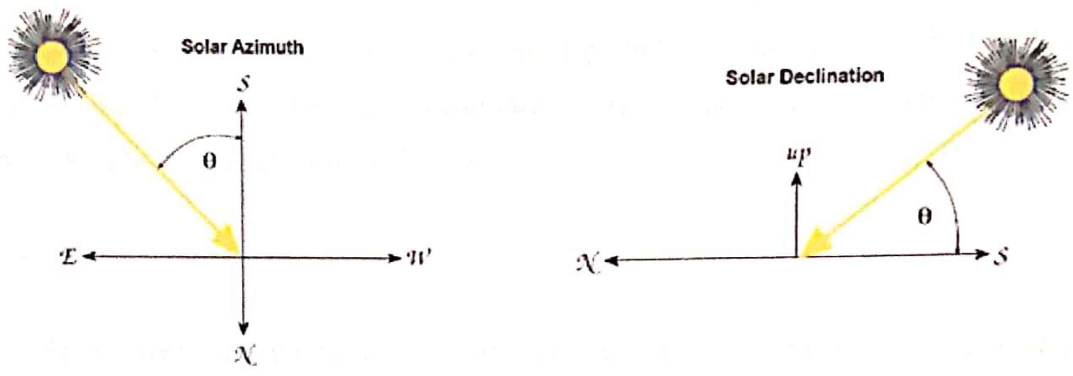


Fig2.1 Azimuth (left) and Declination (right) angles

2.4 Common photovoltaic applications:

In buildings Typically, an array is incorporated into the roof or walls of a building and roof tiles with integrated PV cells can now be purchased where it can be used for lighting, heating and other applications, Also in remote or mountainous areas PV may be the preferred possibility for generating electricity, PV may be used together with wind, diesel generators and/or hydroelectric power. In such off-grid circumstances batteries are usually used to store the electric power.

Another application is in transportation PV has traditionally been used for auxiliary power in space. PV is rarely used to provide motive power in transport applications, but is being used increasingly to provide auxiliary power in boats and cars. Recent advances in solar cell technology, however, have shown the cell's ability to administer significant hydrogen production, making it one of the top prospects for alternative energy for automobiles, in water pumping water is one of the most competitive arenas for PV power since it is simple, reliable, and requires almost no maintenance. Agricultural watering needs are usually greatest during sunnier periods when more water can be pumped with a solar system.

Electric Fences PV power can be used to electrify fences for livestock and animals, also in lighting PV powered lighting systems are reliable and a low cost alternative. Security, billboard sign, area, outdoor and streets lighting are all viable applications for PV.

2.5 Advantages

"Solar electric generation has the highest power density (global mean of 170 W/m^2) among renewable energies; solar power is pollution free during use. Production end wastes and emissions are manageable using existing pollution controls. End-of-use recycling technologies are under development, Facilities can operate with little maintenance or intervention after initial setup.

Solar electric generation is economically superior where grid connection or fuel transport is difficult, costly or impossible. Examples include satellites, island communities, remote locations and ocean vessels, once the initial capital cost of building a solar power plant has been spent, operating costs are extremely low compared to existing power technologies.

Compared to fossil and nuclear energy sources, very little research-money has been invested in the development of solar cells, so there is much room for improvement. Nevertheless, experimental high efficiency solar cells already have efficiencies of over 40% and efficiencies are rapidly rising while mass production costs are rapidly falling." [4]

2.6 Disadvantages

Solar electricity is often initially more expensive than electricity generated by other sources; solar electricity is not available at night and is less available in cloudy weather conditions from conventional silicon based technologies. Therefore, a storage or complementary power system is required. However, the use of germanium in amorphous silicon-germanium thin film solar cells provides residual power generating capacity at night due to background infrared radiation, Solar cells produce DC which must be converted to AC (using a grid tie inverter) when used in currently existing distribution grids. This incurs an energy loss of 4-12%.

Chapter 3

Mechanical Design

3.1 General Outlook
3.2 Stress Analysis
3.3 Dynamic Analysis
3.4 System Inertia

3.1 General Outlook

It took about two weeks to change the concept and the methodology of the mechanical design, the design of the project that was intended to be made in the first semester as shown in fig (3.1) has been changed to be as shown in fig (3.2), in addition of being easier to implement the new design has some advantages over the old one, it has less components and so needs less torque to move it.

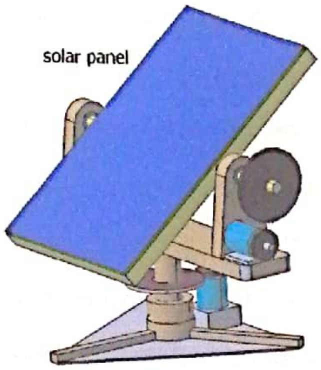


Fig 3.1 old mechanical design

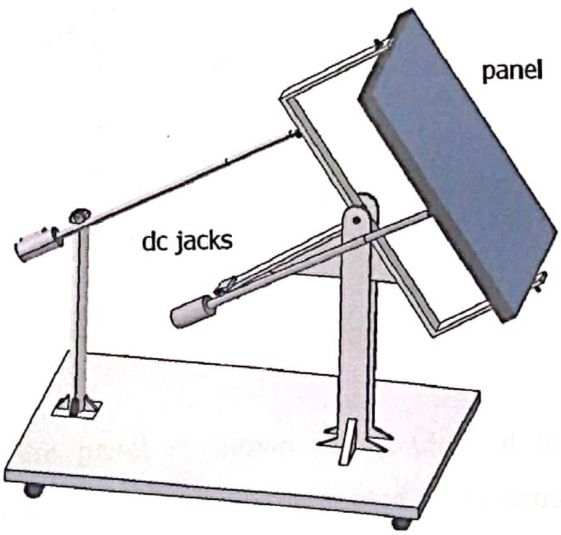


Fig 3.2 new mechanical design

This structure aimed to reduce the high stress expected on the lower shaft in the old design, in addition the actuators used have internal screw gears that's why the whole system got a very high back drivability such that reducing the effect of the wind or other external effects that might move the panel toward undesired orientations.

Those actuators used are characterized by being slow and easily controlled so they are fit for the goal of accurate and smooth tracking for the slow motion of the sun.

The structure of this solar tracker consists mainly of two parts will be rotated by two linear actuators (dc power jacks), One jack will move linearly to rotate the frame that holds the panel around the Z axis (daily east to west solar motion which is called solar azimuth); the other will move linearly in order to rotate the U-part (that carries the frame) around the Y axis (yearly north to south solar motion is called solar declination) as shown in fig (3.3), Both motions will be controlled by a microcontroller such that the panel faces the sun all the time as will be shown in chapter 5.

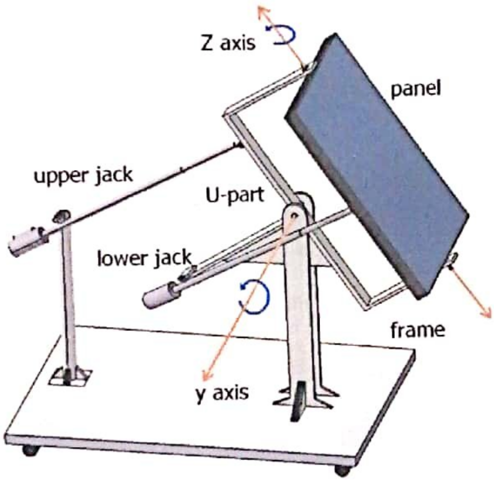


Fig 3.3 axes of rotations

The frame that holds the panel is shown in fig (3.4), it is connected to the U-part through bearings up and down such that it can be rotated easily without friction.

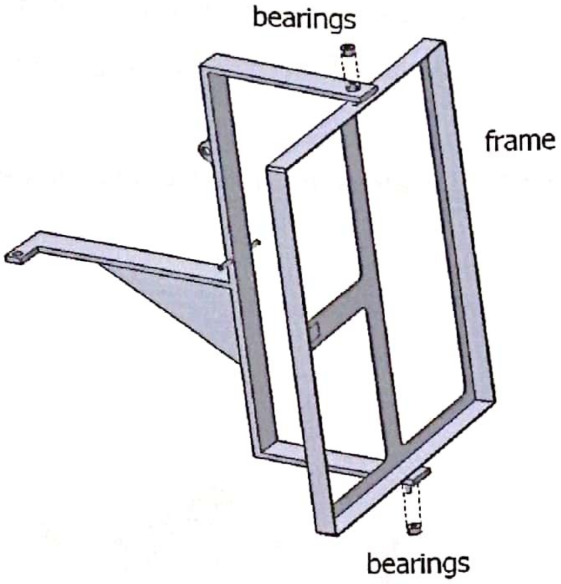


Fig 3.4 frame and bearings

The U-shaped part will be used to change the declination angle of the panel through the upper jack motion forward and backward, to reduce friction and torque needed bearings are also used to connect the U part and the supports that hold the system as shown in fig (3.5).

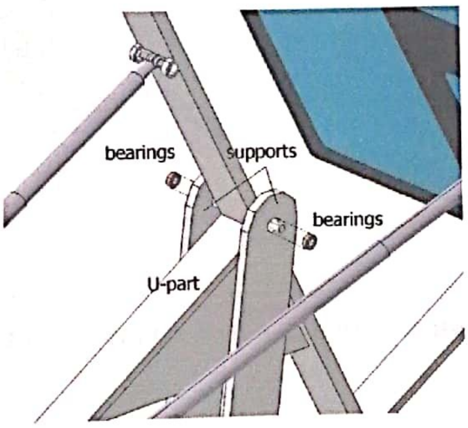


Fig 3.5 upper jack and U part

The mechanical structure of the system was chosen to be made of Aluminum for the special characteristics this metal has, like being soft, lightweight, available, corrosion resistant and its ability to be easily machined, however its high cost relative to other metals such as cast iron might be the only disadvantage considered in this choice.

The design was machined and implemented as shown in fig (3.6).

Fig 3.6 system mechanical implementation

3.2 Stress Analysis

3.2.1 Wind analysis

The stress analysis of the system will take into consideration the effect of the wind pressure as a basic load, the maximum dynamic pressure of the wind on the solar panel based on the maximum wind velocity in Hebron city can be calculated as follows

$$P_{Wind} = \frac{1}{2}\rho v^2 = \frac{1}{2} * 1.2 * 36^2 \approx 0.8\ kN/m^2 \qquad 3.1$$

Where P_{Wind} is the dynamic pressure, ρ is the density of air ($\rho = 1.2\ Kg/m^3$) and v is the velocity of the wind (in Hebron $v_{max} = 36\ m/s$).

Now considering the maximum effect of this pressure on the system will be found assuming the panel to be facing the wind directly as shown in fig (3.7).

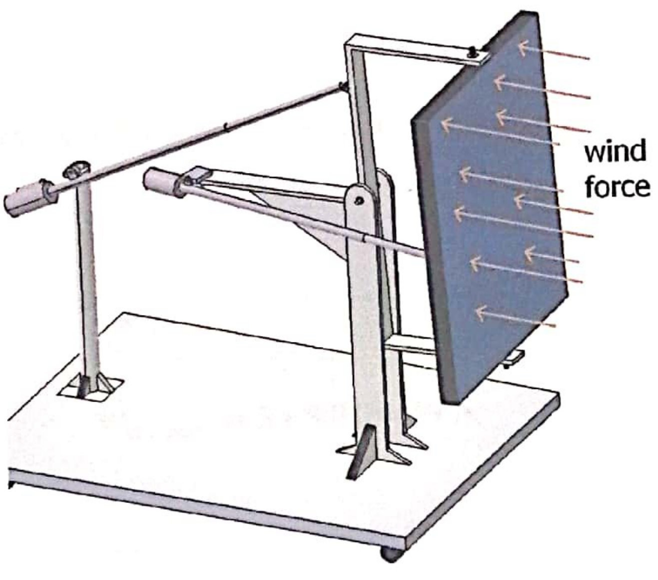


Fig 3.7 wind and panel orientation

With a pressure coefficient $C_P = 2.1$ (according to the DIN 1055 part 4 data) the force of the wind is found to be

$$F_{Wind} = C_P * P_{Wind} * A_{panel} \quad 3.2$$

$$F_{Wind} = 2.1 * 0.8 * 10^3 * 0.532 * 0.658$$

$$F_{Wind} = 588\ N$$

Where F_{Wind} is the force exerted by wind, A_{panel} is the area of the panel ($length =$ 65.8 mm, $width =\ 53.2\ mm$).

3.2.2 Force and stress analysis of the system

As shown in fig (3.8) the basic loads that affect the system are the weight of the lower jack ($W_{l.jack}$), the weight of the U-part (W_{U-part}), the weight of the panel (W_{panel}) and the wind force.

These unknowns were found via experimental tests and using the CATIA software and their values are as follows

$$W_{l.jack} = 3.5 * 9.81 = 34.3\ N$$

$$W_{U-part} = 5 * 9.81 = 49\ N$$

$$W_{panel} = 4.5 * 9.81 = 44.1\ N$$

$F_{U.jack}$ is the force exerted by the upper jack on the structure, it is found by using the two force member method so the direction of the net force has the same direction as the member axis, the angle between $F_{U.jack}$ vector with vertical line is found using CATIA software to be

θ=65°, so the value of this force can be calculated by taking the moment about point c shown in fig (3.8) where

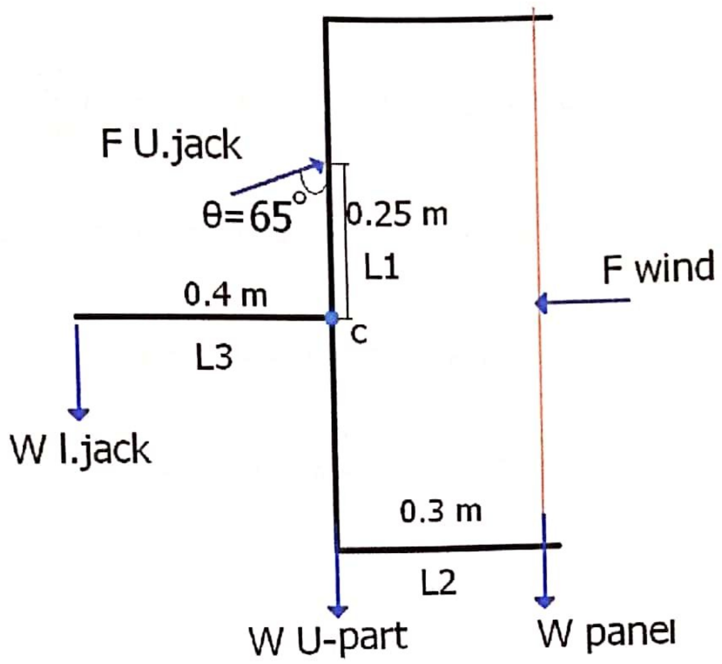


Fig 3.8 force analysis

$$\sum M_c = F_{U.jack} \sin\theta \, L_1 + w_{Panel} * L_2 - W_{l.jack} * L_3 = 0 \qquad 3.3$$

$$\sum M_c = F_{U.jack} * \sin 65 * 0.2 + 44.1 * 0.3 - 34.3 * 0.4 = 0$$

$$F_{U.jack} = 2.7\ N$$

In order to find the maximum shearing stress on the shafts that holds the U-part with other parts connected to, the resultant force exerted on it has to be found as shown in fig (3.9) as follows

For the X component

$$\sum F_X = 0 \qquad 3.4$$

$$\sum F_X = C_X + F_{U.jack} \sin\theta - F_{wind} = 0$$

Where C_X is the horizontal component of the net force on shaft.

$$C_X = -F_{U.jack} \sin\theta + F_{wind}$$

$$C_X = -2.44 + 588 = 585.5 \text{ N}$$

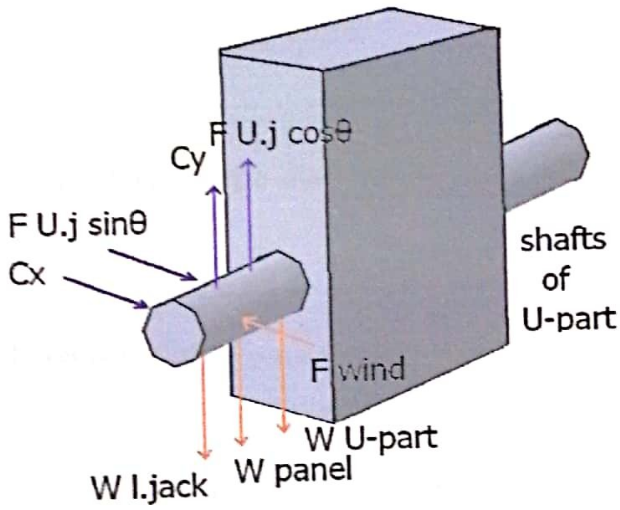


Fig 3.9 shear force on shafts

For the Y component

$$\sum F_Y = 0 \qquad 3.5$$

$$C_Y = -F_{U.jack} \cos\theta + W_{l.jack} + W_{U-part} + W_{Panel}$$

Where C_Y is the vertical component of the net force on shaft.

$$C_Y = -1.14 + 34.3 + 49 + 44.1 = 126.3 \text{ N}$$

The resultant force on the shaft is

$$C_{res} = \sqrt{{C_X}^2 + {C_Y}^2} \qquad 3.6$$

$$C_{res} = \sqrt{585.5^2 + 126.3^2} = 599 \approx 600 \text{ N}$$

The allowable stress on the shaft is found to be

$$\tau_{allowable} = \frac{F_{shear}}{A_{shaft}} \qquad 3.7$$

Where F_{shear} is the shear force on the shaft and A_{shaft} is the area of the cross section of the shaft.

As the U part is hold on two shafts F_{shear} can be calculated as shown

$$F_{shear} = \frac{C_{res}}{2} = 300 \text{ N} \qquad 3.8$$

For aluminum the shear yield stress $\tau_{yield} = 95$ MPa and for a factor of safety of 20 the allowable shear stress of the shaft is

$$\tau_{allowable} = \frac{\tau_y}{F.S} \qquad 3.9$$

$$\tau_{allowable} = \frac{95 \text{ MPa}}{20} = 4.75 \text{ MPa}$$

Then the suitable cross sectional area of the shaft is calculated (according to eq3.7) by

$$A_{shaft} = \frac{F_{shear}}{\tau_{allowable}}$$

$$A_{shaft} = \frac{300}{4.7 * 10^{6}} = 6.38 * 10^{-5} m^{2}$$

From which the diameter is found to be

$$d = \sqrt{\frac{4A}{\pi}} = 8.96\ mm \qquad 3.10$$

And so a 9mm diameter shaft is to be used based on the available bearings size, for this shaft the bearing where chosen to be as shown in fig (3.10)

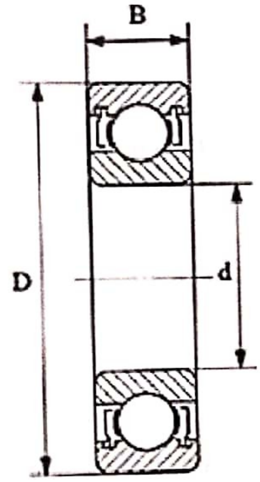


Fig 3.10 bearings dimension

Where

$$B = 7\ mm$$

$$D = 24\ mm$$

$$d = 9mm$$

For which the bearing stress on the supports can be calculated as follows

$$\sigma_{bearing} = \frac{F_{shear}}{A_{bearing}} \qquad 3.11$$

Where F_{shear} is the exerted force on supports and $A_{bearing}$ is the cross section area of the bearings used.

$$A_{bearing} = B * D$$

$$A_{bearing} = 0.024 * 0.007 = 168 * 10^{-6} m^2$$

$$\sigma_{bearing} = \frac{300}{168 * 10^{-6}} = 1.78\ MPa$$

As the supports are made of cast iron, this metal has yield strength of 230 MPa for which a 10 mm thickness for the supports is a good and safe option to choose.

For the maximum shearing stress at the frame's shafts the resultant force exerted on them by wind has to be found, where

$$F_{shear\ of\ the\ (upper\ \backslash lower)\ shaft} = \frac{1}{2} F_{wind} = \frac{588}{2} = 294\ N \qquad 3.12$$

Back to eq3.9 for aluminum the shear yield stress $\tau_{yield} = 95$ MPa and for a factor of safety of 20 the allowable shear stress of the shaft is

$$\tau_{allowable} = \frac{\tau_y}{F.S}$$

$$\tau_{allowable} = \frac{95\ \text{MPa}}{20} = 4.75\ \text{MPa}$$

Then the suitable cross sectional area of the shaft is calculated by

$$A_{shaft} = \frac{F_{shear}}{\tau_{allowable}}$$

$$A_{shaft} = \frac{300}{4.7 * 10^6} = 6.38 * 10^{-5} m^2$$

From which the diameter is found to be

$$d = \sqrt{\frac{4A}{\pi}} = 8.96\ mm$$

And so a 9mm diameter shaft is to be used based on the available bearings size, for which a $7\ mm * 24\ mm * 9\ mm$ bearing where chosen like the previous case.

The bearing stress on the U-part arms can be calculated as follows

$$\sigma_{bearing} = \frac{F_{shear\ of\ wind\ force}}{A_{bearing}} \qquad 3.13$$

Where $F_{shear\ of\ wind\ force}$ is the exerted force by wind on U-parts arms and $A_{bearing}$ is the cross section area of the bearings used.

$$A_{bearing} = 168 * 10^{-6} m^2$$

$$\sigma_{bearing} = \frac{294}{168 * 10^{-6}} = 1.75\ MPa$$

As the U-part is made of Aluminum, this metal has yield strength of 95 MPa for which a 10 mm thickness for the arms is a good and safe option to choose.

3.3 Dynamics Analysis

Mass moment of inertia of the whole system is found in order to build the mathematical model needed.

In general

$$I = \bar{I} + md^2 \qquad 3.14$$

Where I is the mass moment of inertia, $\bar{I}$ is the mass moment of inertia about mass center axis, m is the mass of the body and d is the radial distance between the mass center axis and another parallel axis of rotation.

Dynamics analysis of the panel

Since the panel will rotate in two directions around Z axis and Y axis its inertia tensor is given by

$$\begin{bmatrix} I_{XX} & -I_{XY} & -I_{XZ} \\ -I_{YX} & I_{YY} & -I_{YZ} \\ -I_{ZX} & -I_{ZY} & I_{ZZ} \end{bmatrix}$$

Where I_{XX}, I_{YY} *and* I_{ZZ} are the principle moment of inertia components of the panel around X, Y and Z axes respectively and I_{XY}, I_{XZ}, I_{YX}, I_{YZ}, I_{ZX} and I_{ZY} are the product of inertia components of the panel.

In order to compute the loading effect (moment) of the panel on the system, the general moment equation has to be found where

$$\sum M = \dot{H} \qquad 3.15$$

Where $\sum M$ is the summation of the moment components and $\dot{H}$ is the angular momentum derivative

For the panel this equation can be implemented as follows

$$\begin{bmatrix} M_x \\ M_y \\ M_Z \end{bmatrix} = \begin{bmatrix} \dot{H}_x \\ \dot{H}_y \\ \dot{H}_Z \end{bmatrix} + \begin{bmatrix} 0 & H_Z & -H_Y \\ -H_Z & 0 & H_x \\ H_Y & -H_x & 0 \end{bmatrix} \cdot \begin{bmatrix} w_X \\ w_y \\ w_Z \end{bmatrix} \quad 3.16$$

Where M_x, M_Y *and* M_z are the moment components of the panel, $\dot{H}_x$, $\dot{H}_Y$ and $\dot{H}_Z$ are the angular momentum rate of change components, H_X, H_Y and H_Z are angular momentum components and finally w_X, w_Y and w_Z are the angular velocity components of the panel.

The angular momentum components and their derivatives are as follows

In X direction

$$H_x = I_{XX}w_X - I_{XY}w_Y - I_{XZ}w_Z \quad 3.17$$

$$\dot{H}_x = I_{XX}\dot{w}_X - I_{XY}\dot{w}_Y - I_{XZ}\dot{w}_Z \quad 3.18$$

In Y direction

$$H_Y = -I_{YX}w_X + I_{YY}w_Y - I_{YZ}w_Z \quad 3.19$$

$$\dot{H}_Y = -I_{YX}\dot{w}_X + I_{YY}\dot{w}_Y - I_{YZ}\dot{w}_Z \quad 3.20$$

In Y direction

$$H_Z = -I_{ZX}w_X - I_{ZY}w_Y + I_{ZZ}w_Z \quad 3.21$$

$$\dot{H}_Z = -I_{ZX}\dot{w}_X - I_{ZY}\dot{w}_Y + I_{ZZ}\dot{w}_Z \quad 3.22$$

By substitution eq (3.16) can be written as shown

$$\begin{bmatrix} M_x \\ M_y \\ M_Z \end{bmatrix} = \begin{bmatrix} I_{XX} & -I_{XY} & -I_{XZ} \\ -I_{YX} & I_{YY} & -I_{YZ} \\ -I_{ZX} & -I_{ZY} & I_{ZZ} \end{bmatrix} \cdot \begin{bmatrix} \dot{w}_X \\ \dot{w}_y \\ \dot{w}_Z \end{bmatrix} + \begin{bmatrix} 0 & H_Z & -H_Y \\ -H_Z & 0 & H_x \\ H_Y & -H_x & 0 \end{bmatrix} \cdot \begin{bmatrix} w_X \\ w_y \\ w_Z \end{bmatrix} \quad 3.23$$

Writing the moment equation in terms of inertia components results in

$$\begin{bmatrix} M_x \\ M_y \\ M_Z \end{bmatrix} = \begin{bmatrix} I_{XX} & -I_{XY} & -I_{XZ} \\ -I_{YX} & I_{YY} & -I_{YZ} \\ -I_{ZX} & -I_{ZY} & I_{ZZ} \end{bmatrix} \cdot \begin{bmatrix} \dot{w}_X \\ \dot{w}_y \\ \dot{w}_Z \end{bmatrix} + \begin{bmatrix} 0 & I_{ZZ}\omega_Z & -I_{YY}\omega_Y \\ -I_{ZZ}\omega_Z & 0 & -I_{XZ}\omega_Z \\ I_{YY}\omega_Y & I_{XZ}\omega_Z & 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ w_y \\ w_Z \end{bmatrix} \quad 3.24$$

By finding the inertia components of the panel around the three axes the whole loading effect of it can be figured, from fig (3.11) the principle inertia components along with product of inertia components will be calculated, then these components will be compensated in eq (3.23).

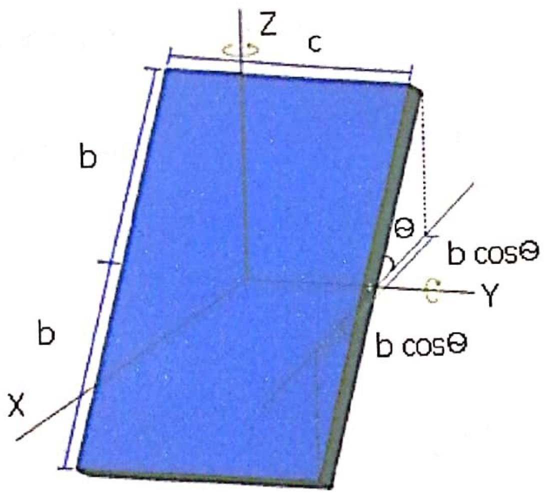


Fig 3.11 panel dimensions

For our system the thickness of the panel will be neglected in our calculations as it is small relative to its length (2b) and width (c), by referring to fig (3.11) the inertia component in X direction

$$I_{XX} = \frac{m_{panel}}{12}(c^2) + 0 \quad 3.25$$

Where m_{panel} and c are the mass and the width of the panel respectively.

For the inertia component in Y direction

$$I_{YY} = \frac{m_{panel}}{12}(2b\cos\Theta)^2 + 0 \tag{3.26}$$

Where b is the half of the length of the panel and Θ is the angle of inclination of the panel from horizontal.

For the inertia component in Z direction

$$I_{ZZ} = \frac{m_{panel}}{12}((2b\cos\Theta)^2 + c^2) + 0 \tag{3.27}$$

For the product of inertia components $(I_{XY} = I_{YX})$, $(I_{ZY} = I_{YZ})$ and $(I_{ZX} = I_{XZ})$ their values can be found by referring again to fig (3.11).

From fig (3.12) the panel inertia component refer to X and Z coordinate axes can be calculated as shown

$$I_{XZ} = \int xzdm \tag{3.28}$$

$$I_{XZ} = \int_{-b}^{b}(-l\cos\Theta)(l\sin\Theta)2c\rho dl = -\frac{1}{3}c\rho b^3\sin 2\Theta \tag{3.29}$$

where ρ is the mass per unit area .

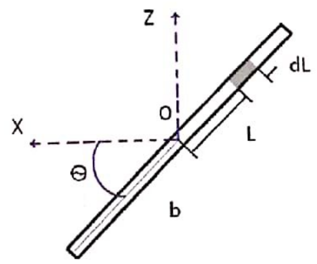


Fig 3.12 side view of the panel

From fig (3.13) the panel inertia component refer to X and Y coordinate axes can be calculated by considering a small mass with $dm = \rho t\ dxdy$, where ρ is the mass density and t is the thickness as shown

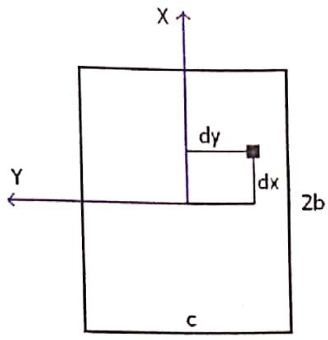


Fig 3.13 Top view of the panel

$$I_{XY} = \int xydm \quad 3.30$$

$$I_{XY} = \rho t \iint_{-b}^{b} xy\ dxdy \quad 3.31$$

$$I_{XY} = \rho t \int_{-0.5}^{0.5} y\ dy\left(\frac{b^2-b^2}{2}\right) = 0 \quad 3.32$$

From fig (3.14) the panel inertia component refer to Z and Y coordinate axes can be calculated as shown by considering a small mass with $dm = \rho t\ dzdy$, where ρ is the mass density and t is the thickness as shown

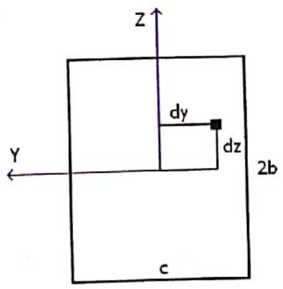


Fig 3.14 front view of the panel

$$I_{YZ} = \int yzdm \qquad 3.33$$

$$I_{YZ} = \rho t \iint_{-b}^{b} zy \, dzdy \qquad 3.34$$

$$I_{YZ} = \rho t \int_{-0.5}^{0.5} y \, dy (\frac{b^2 - b^2}{2}) = 0 \qquad 3.35$$

Now after finding the total inertia components we can find the moment components in addition to the inertia tensor taking into consideration that the panel rotates around Y and Z axes and so

$w_x = \dot{w}_x = 0$, in addition ($I_{ZY} = I_{YZ} = 0$) and ($I_{YX} = I_{XY} = 0$) by substitution in eq (3.24), then the moment equation can be written as

$$\begin{bmatrix} M_x \\ M_y \\ M_Z \end{bmatrix} = \begin{bmatrix} I_{XX} & 0 & -I_{XZ} \\ 0 & I_{YY} & 0 \\ -I_{ZX} & 0 & I_{ZZ} \end{bmatrix} \cdot \begin{bmatrix} 0 \\ \dot{w}_y \\ \dot{w}_Z \end{bmatrix} + \begin{bmatrix} 0 & I_{ZZ}\omega_Z & -I_{YY}\omega_Y \\ -I_{ZZ}\omega_Z & 0 & -I_{XZ}\omega_Z \\ I_{YY}\omega_Y & I_{XZ}\omega_Z & 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ w_y \\ w_Z \end{bmatrix} \qquad 3.36$$

If we take the load moments in k, j directions they will be as follows

In Y direction

$$M_Y = I_{YY}\dot{w}_Y - I_{XZ}{w_Z}^2 \qquad 3.37$$

Since the system will be controlled such that it can rotate in one direction at a time then $w_Z = 0$ when the panel rotates in Y direction and so

$$M_Y = I_{YY}\dot{w}_Y = I_{YY}\ddot{\theta}_Y = \frac{m_{panel}}{12}(2b\cos\Theta)^2\ddot{\theta}_Y \qquad 3.38$$

Where I_{YY} is the mass moment of inertia of the panel around Y axis.

In Z direction

$$M_Z = I_{ZZ}\dot{w}_Z + I_{XZ}w_Z w_y \quad 3.39$$

Where $w_Y = 0$ when the panel rotates around Z direction, then

$$M_Z = I_{ZZ}\dot{w}_Z = I_{ZZ}\ddot{\theta}_Z = \frac{m_{panel}}{12}((2b\cos\Theta)^2\ddot{\theta}_Z \quad 3.40$$

Where I_{ZZ} is the mass moment of inertia of the panel around Z axis

3.4 System Inertia

As it is seen from the equations of the mass moment of inertia these inertias are related to the angle theta of the panel, which varies through the day and so changing the mass moment of inertia, the average value is to be considered in this case.

The calculated values of mass moment of inertia will be used in the mathematical modeling of the system in the control chapter, the system has two motions and so two sup systems one around the Z axis and the other around the Y axis, for the first one it has just one moving part which is the panel around it's center axis as shown in fig (3.15).

As the inertia of the panel around Z axis is expressed by $I_{ZZ} = \frac{m_{panel}}{12}((2b\cos\Theta)^2 + c^2)$, then for a range of angle 90°-5° the average mass moment of inertia of the panel about the Z-axis is found using excel to be $I_{zz-panel\ (av)} = 0.2016\ kg.m^2$.

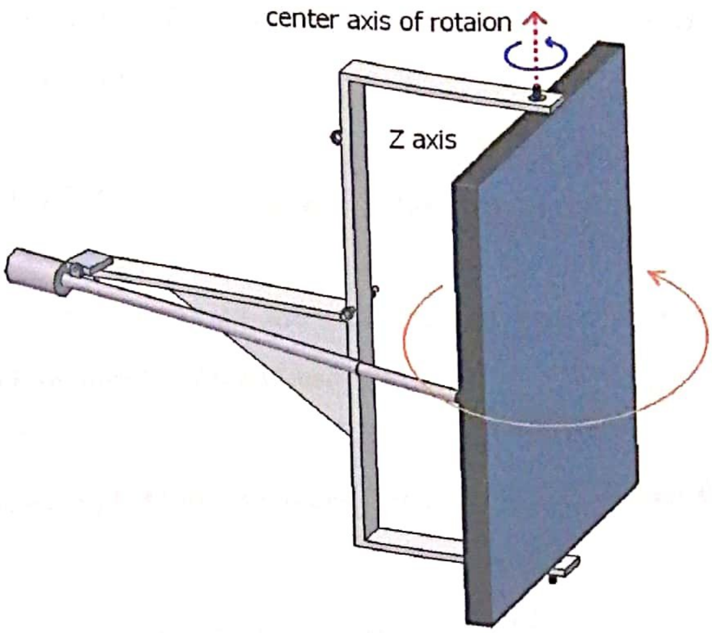


Fig 3.15 first rotating system

For the other sup system it has three basic moving parts as shown in fig (3.16), the U part which considered to rotate about it's center axes and so no need for the parallel axis theorem, however this is not the case for the panel and the lower jack that rotate around an axes different from their central one, for this reason the calculations here are a little bit more complex than before.

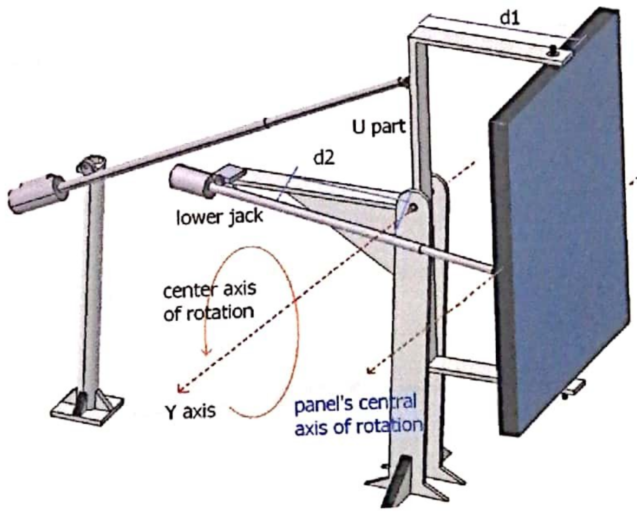


Fig 3.16 second rotating system

The total mass moment of inertia about Y-axis of the system is calculated according to the following equation

$$I_{yy} = I_{panel\ (Y)} + I_{U-part} + I_{lower\ jack} \quad 3.41$$

Where $I_{panel\ (Y)}$ is the inertia of the panel about this Y axis, I_{U-part} the inertia of the U-part, $I_{lower\ jack}$ is the inertia of the lower jack

But the value of $I_{panel\ (Y)}$ is to be calculated through the parallel axis theorem

$$I_{panel\ (Y)} = I_{Panel\ at\ CG} + md_1{}^2 \quad 3.42$$

Where m is the mass of the panel and d_1 shown in fig (3.16) is the distance between the center of gravity axis and the system rotational axis

Here also the panels inertia is an angle dependent value such that it's value varies as the panel changes it's orientation, for that the panel's inertia about it's central axis $I_{Panel\ at\ CG}$ is averaged for a range of angles from 90°-5° such as was done for the Z axis, this average value was found to be

$$I_{YY-panel\,(av)} = I_{Panel\ at\ CG} = 0.2025\ kg.m^2$$

Back to eq (3.42)

$$I_{panel\ (Y)} = 0.2025 + 5 * 0.3^2$$

$$I_{panel\ (Y)} = 0.45\ Kg.m^2$$

For the jack inertia about the same axis, the jack is considered to be a cylinder as shown in fig (3.17) since it is the closest shape to the jack then its inertia is calculated through the following equation

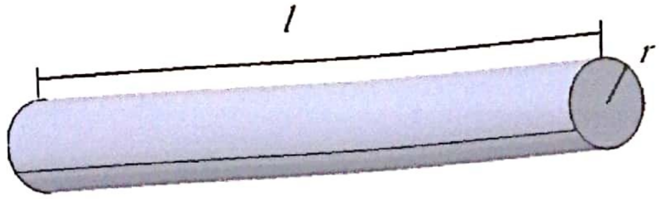


Fig 3.17 cylinder inertia dimensions

$$I_{jack} = 0.25 * m_{jack} * r^2 + \frac{1}{12} * m_{jack} * l^2 + m_{jack} * d^2 \qquad 3.43$$

Where m_{jack} is the mass of the jack, r is the radius of the jack cylinder, l is the length of the jack, d_2 shown in fig (3.16) is the distance between the axis of rotation and the axis of the center of gravity of the jack.

$$I_{jack} = 2.68 * 10^{-4} + 0.105 + 0.428 = 0.534\, Kg.m^2$$

Finally the inertia of the U-part is calculated by using the CATIA software and was found to be

$$I_{U-part} = 0.24\, Kg.m^2$$

Back to eq (3.41) the total mass moment of inertia about the Y-axis is the algebraic sum of the previous calculations which yields

$$I_{yy} = 1.426\, Kg.m^2$$

Chapter 4

Electrical implementation

4.1 Solar system implementation

4.2 Electrical and Electronic system components

4.3 Electrical Implementation

4.1.2 Charging controller:

The charge controller is the component that control the work of solar system, it manage the charging and discharging processes, it limits the rate at which electric current is added to or drawn from electric battery. It prevents overcharging and may prevent against overvoltage, which can reduce battery performance or lifespan, It may also prevent completely draining ("deep discharging") a battery, the same company that was mailed for buying the panel has also such controllers in addition to the battery.

The Steca Solsum 6.6c shown in fig (4.2), is the charger that suits the chosen panel as it can work with 5 to 10 amp solar charging and load current capacity, full details and operation description is listed in the charger data sheet shown in appendix (B).

Fig 4.2 overcharge controller

4.1.3 Storing Battery:

It is essential for any solar system to have a storage unit, a 12 V was brought with the panel and the over charge controller, as the system is self powered this battery will feed the actuators used, those can be operated with this level of voltage at a reasonable level of speed, the current can be drawn from the battery at an 40Ah which describes the relation between the current drawn and the time it consumed to draw it, if for example a 2.33 A is needed for the load then this battery can serve the system for a 15 continuous hours which is more than enough for this system with actuators need less than 1 amp to handle it's motion.

The battery shown in fig (4.3) is to be connected to the overcharge controller which controls it's charging and discharging, the load will never be connected directly to the battery, instead specific ports for the load are available in the charger device, and the battery specifications are also described in its data sheet in appendix (C).

Fig 4.3 system battery

4.1.4 Solar system installation and wiring:

Installation of the solar components is done by referring to the installation manuals of the panel and the charger provided by the suppliers and available on the internet websites for these products they are also listed in appendix (D), attention has been taken about the wiring of these components and their installation.

As described in the manual the battery is connected first to the charger then the panel, however the panel is to be removed first then the battery if the system is to be removed or modification in its location is done, the wires used are 14 AWG (American wire gauge) cables with 1.628 mm diameter as recommended to reduce the voltage drop to minimum, the diagram shown in fig (4.4) shows a simple layout of the solar system structure

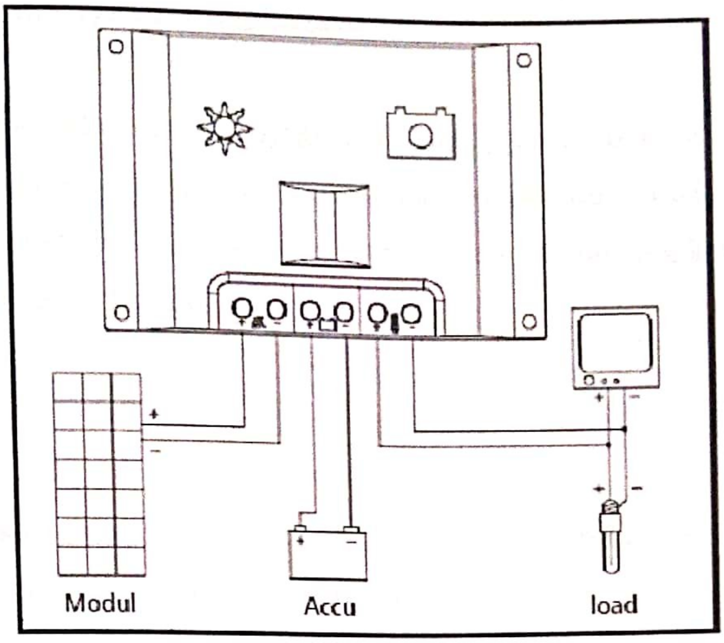


Fig 4.4 layout of the solar system installation

For the installation of the solar system components the battery and the charge controller are placed in a sealed medium size closet to provide a sun protection with holes made inside it for better air ventilation as shown in fig (4.5), it is also designed to protect the control and storage units from other external effects such as sparks and rain.

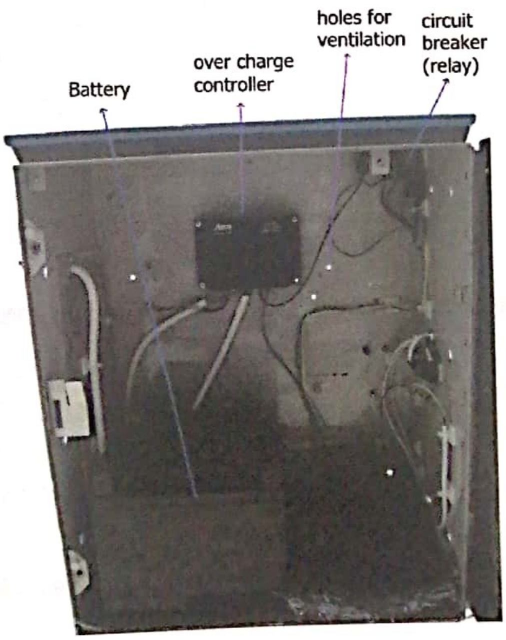


Fig 4.5 closet with control unit

4.2 Electrical and Electronic system components

The electrical and electronic systems of this project consist mainly of three basic components, the actuators, the sensors and the control unit, each of these will be explained next in full details, the next section describes the implementation of the whole electrical/electronic parts together.

4.2.1 Actuators:

The actuators used to move the panel are dc power jacks, these jacks shown in fig (4.6) has an internal dc motor with gear system for speed reduction and torque amplification, to which a gear screw for linear motion is connected as shown in fig (4.7), it can reach up to 45 cm.

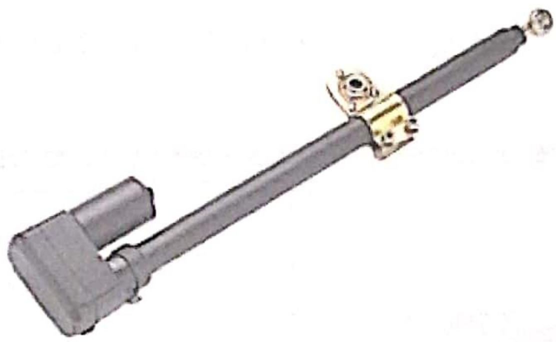


Fig 4.6 dc power jack

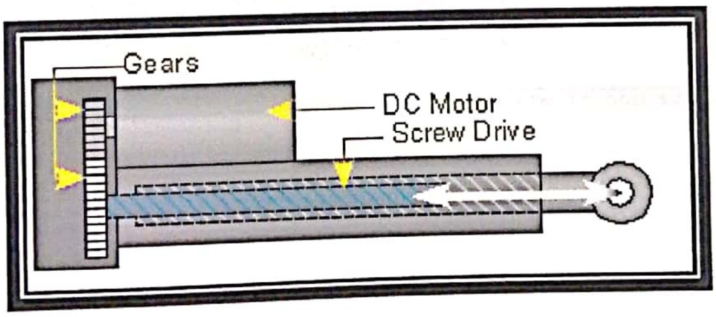


Fig 4.7 internal screw gear of the jack

An important advantage of these jacks, is that they have an internal limit switches shown in fig (4.8) that can be adjusted to cut the power supply off the jack's motor once the maximum or minimum range of motion is reached as shown in fig (4.9), this adjustment is used to protect the mechanical parts from clash .

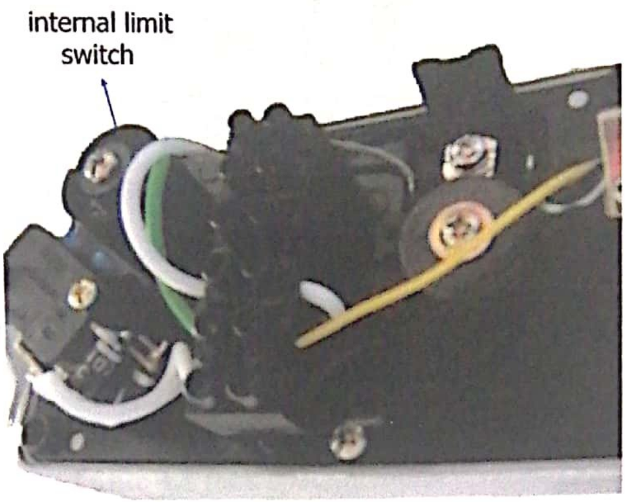


Fig 4.8 internal limit switches of jack

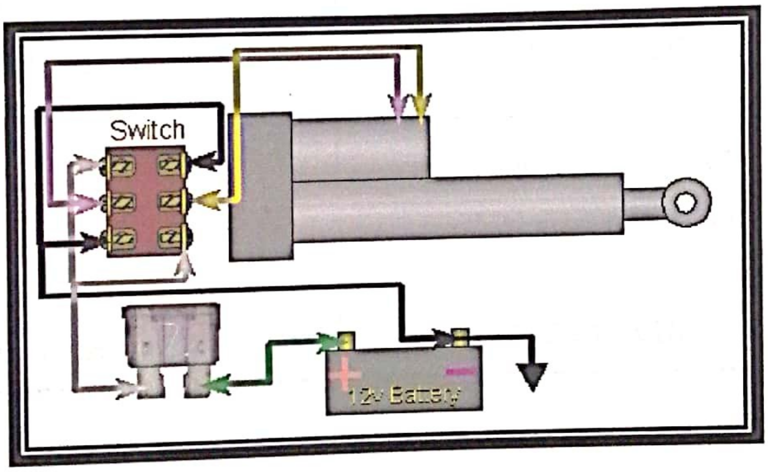


Fig 4.9 jack internal switches

it's important to mention that these jacks already have universal joints, those joints shown in fig (4.10) are very important to apply the needed motion for the system where they allow for the jack to rotate a little while extending or retracting.

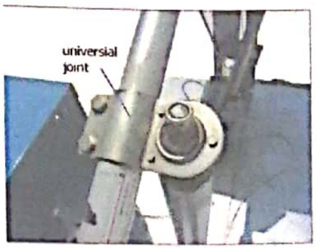


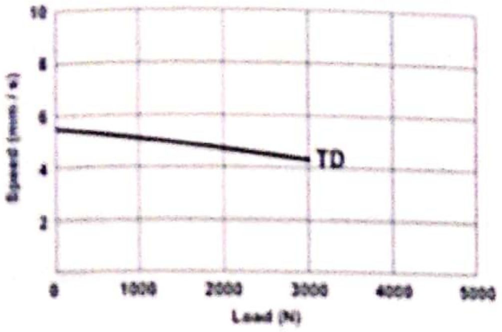
Fig 4.10 jack universal joint

The specifications of these actuators are listed below in table (4.1)

Table 4.1 jack specifications

specifications	
Model	Regular actuator
Input	5-36 VDC
Load Capacity	3000N for 36 VDC
Stroke Length	450mm, 18"
Full Load Speed	4.2mm / sec for 36 VDC
Temperature	-26°C~65°C(-15°F~150°F)
Limit Switch	Adjustable
Static Load	4500N for 36 VDC

The load relations with speed and current are shown in fig (4.11), the maximum voltage this actuator will receive is 12 VDC with the battery of the solar system as the basic and only power source for the whole system such that it achieves being self powered while the speed that corresponds to this level of voltage is about1.4 mm/sec, the measured value for the current drawn did not exceed 1 amp.



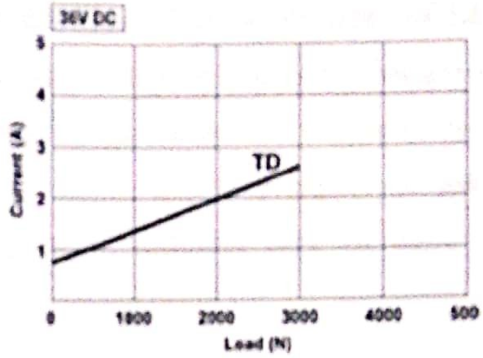


Fig 4.11 jack load relations with speed and current

4.2.2 Sensors:

One of most important parts of any control system is the sensors used; they provide the feed back needed to complete its process, in this system the sensor will be the eye through which the panel tracks the sun path.

Sensor's choice passed through several considerations such as its ability to give a voltage change that is measurable by the PIC microcontroller, cost, size and availability.

First using the Light Detecting Resistor (LDR) shown in fig (4.12) was an option; it is small in size, cheap and has a good range of change in its resistance value due to variation in light intensity up on its surface.

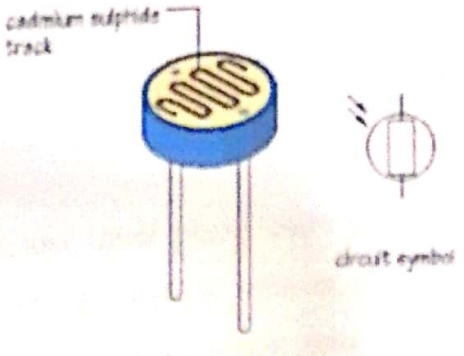


Fig 4.12 LDR

To get better sensitivity for light change the idea of using an array of LDRs was applied, such that the range of change increases as the light's intensity changes over the same sensor, the array shown in fig (4.13) needs bridge circuit to increase the linearity of the output as shown in fig (4.14), this circuit needs a power supply to get voltage output instead of resistance change, that's why using different type of light detectors has been done.

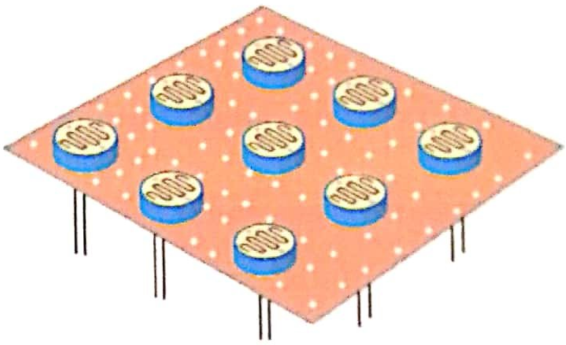


Fig 4.13 LDRs array

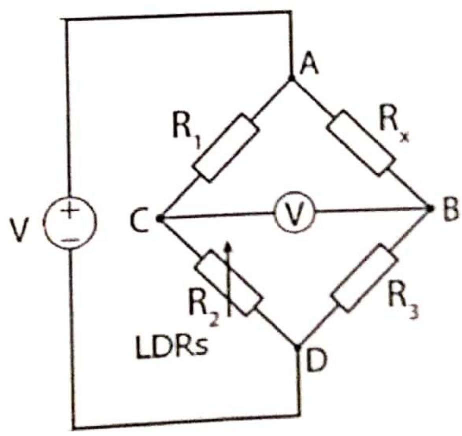


Fig 4.14 bridge circuit with LDR

Another choice was to use small photo cells that are capable of generating their own voltage and current and using them as sensors, searching for source of such cells took some time, until the best available option was found in small car medals (cars accessories) that have small pv cells as shown in fig (4.15) in addition of being cheap where each one cost about 1 dollar only.

Fig 4.15 small car medal

These cells shown in fig (4.16) have no data sheets, that's why several tests have been done to figure out their electrical properties, they generate high voltage relative to their size that could reach up to 7 VDC under the sun rays, with very small current that can't even be measured and so it was possible to use them directly as analog inputs in PIC ADC ports without interface for current limiting, in addition of having an approximate linear change between sun light intensity and the output voltage.

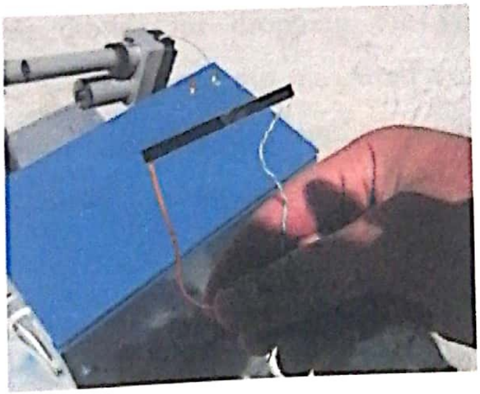


Fig 4.16 small PV cell

The problem that was encountered then is that their output voltage is higher than the one possible for the analog input port in the PIC microchip which is 5 VDC, otherwise all ranges above this limit will be seen by the PIC as one value which is 5

VDC and this would cause problems while comparing the sensors' voltages as will be shown in control chapter.

Trials of reducing cells' voltage have been done, first by trying the voltage divider method via the cell's current as shown in fig (4.17), but it failed since this current was very small, in addition to failure in amplifying it using transistors of different types where the base current coming from the cell was always about zero.

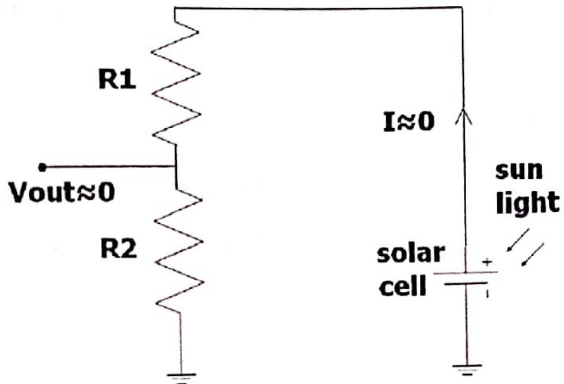


Fig 4.17 voltage divider circuit

Another way was to Use diodes for dropping the voltage, number of series connected diodes as shown in fig (4.18) cause the measured voltage of the cell to drop, however when the circuit shown in fig (4.19) was applied to the PIC, the voltage input to the ADC was zero since the current was not sufficient to overcome the load with the diodes.

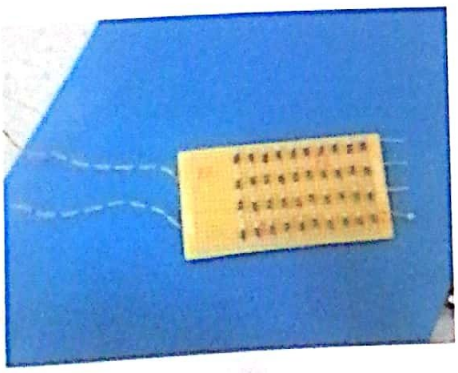


Fig 4.18 Diodes array

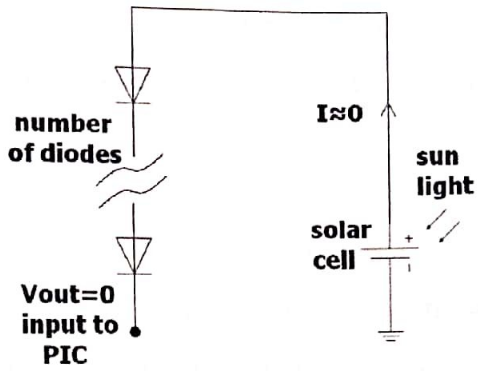


Fig 4.19 voltage reduction circuit using diodes

Finally the idea of using opposite voltage source of small current was used, watches batteries of about 1.5 to 3 VDC were used such that the circuit shown in fig (4.20), succeeded in reducing the cells voltage to be within the 5VDC the PIC sees

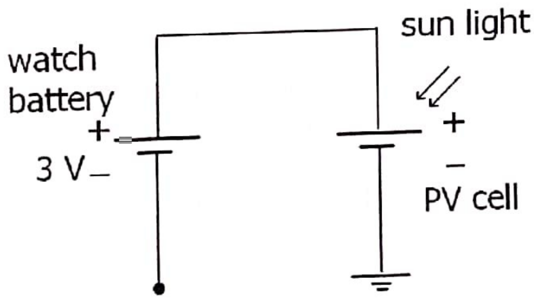


Fig 4.20 voltage reduction circuit using power supply

4.2.3 Control Unit:

The control unit is the part responsible for receiving data from the sensors, processing and controlling the output sent to the actuators, it is the brain of the system that interconnect the previous components together.

The control process includes reading sensors output voltage, processing data and finally sending output to the actuators, each of these will be explained next from the electrical point of view.

Reading sensors values are done through the ADC (Analog to Digital converter) pins that are built inside the PIC chip, as mentioned before the cells used have very small current but measureable voltage such that no interface is required to read their outputs.

4.2.3.1 PIC microchip

The processing of the data and controlling the system is done via the PIC microchip, choosing PIC rather than other control devices and tools such as PC through DAQs or even the PLC is preferred for many reasons, being cheap, small and available are the main features the PIC has over other tools, besides it is perfect solution for small and mobile embedded systems, in addition it needs only 5VDC for the logic supply which can be obtained from the 12V battery of the solar system. However this can't be used for regular PC or PLC which in addition is used for the ON/OFF control that can't handle the real time control and closed loop systems with PID controllers this project needs.

The PIC18f4550 microchip shown in fig (4.21) is chosen for the system, it has 5 I/O ports with 13 10 bit resolution analog input channel and two PWM (Pulse Width Modulation) modules, moreover it has an internal oscillator with 8 user selectable frequencies that range form 31 KHz to 8 MHz and so there is no need for external one to be added to the PIC circuit, more details will be listed in appendix (E).

Fig 4.21 PIC 18f4550

4.2.3.2 Analog output from PIC

After handling the control device to be used in addition to the process of reading the sensors' output through the analog input pins inside the PIC, sending output to the actuators by the control chip has to be dealt with, PIC is a digital device that sends binary data, it doesn't have built in analog output pins like those at the input ports even if some microchip products might have such feature they are not well known and available.

Actuators need analog signal that's why DAC (Digital TO Analog converter) was first tried as a logic solution for this problem, the circuit shown in fig (4.22) shows DAC IC which produces analog output depending on the received binary words from the PIC, the circuit shows also Op-Amps used for amplifying the coming signal from the DAC so it can reach the voltage limit that motors need, after this level the current has also to be amplified to reach at least 1 amp.

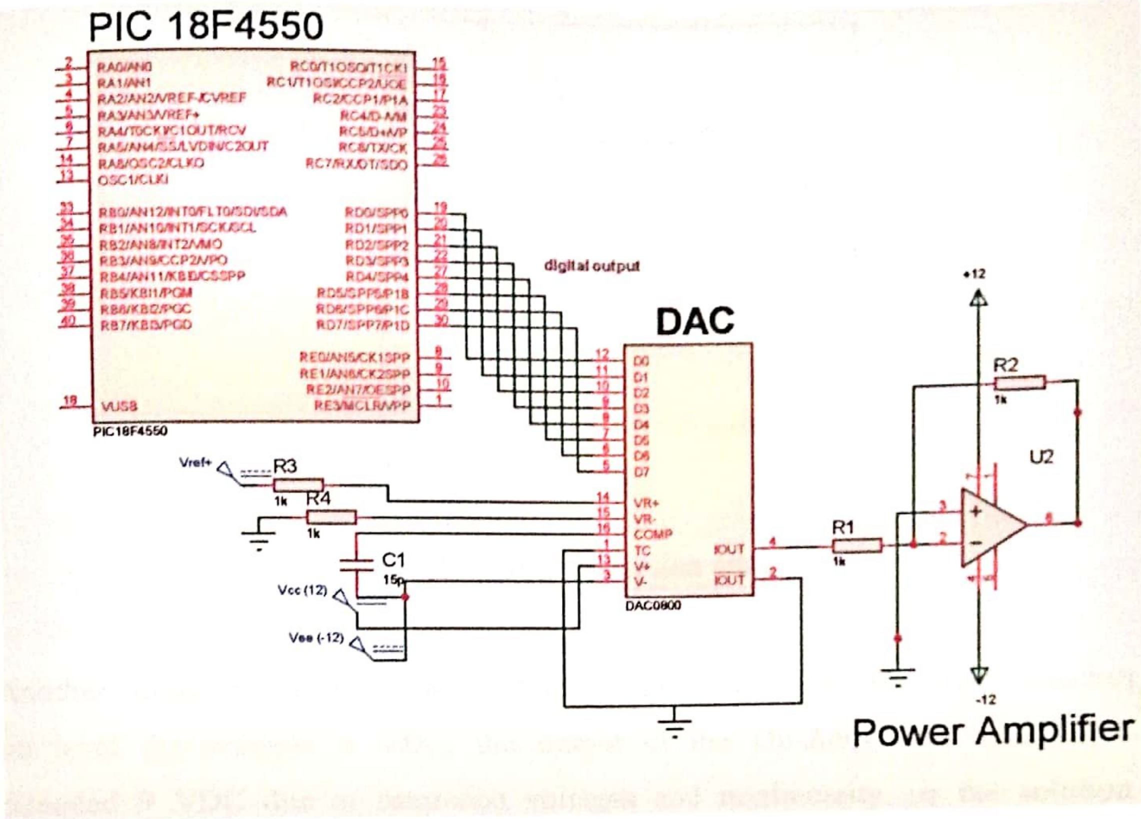


Fig 4.22 DAC circuit

The previous circuit has some problems that make it hard to use the concept of DAC, needing negative supply for the DAC IC, Op-Amps and the power amplifiers might be the biggest problem because the solar system built for the project has only one battery and so generating negative voltage from positive one didn't work although the circuit of 555 timer shown in fig (4.23) makes it possible to have -12 V generated from +12V, but once this voltage is produced it is vanished immediately due to the capacitors used, other circuits for generating negative voltage requires components that are not available in the markets.

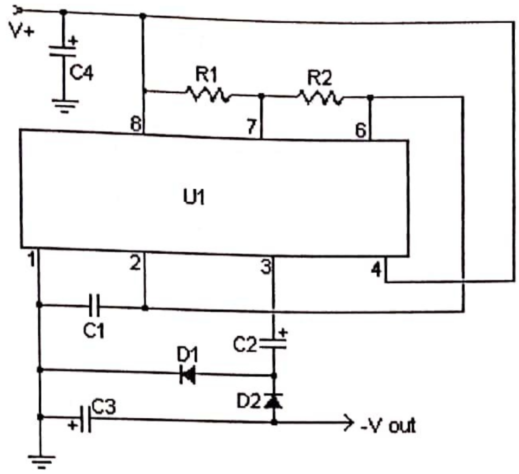


Fig 4.23 555 voltage inversion circuit

Another problem occurred when the voltage out form the DAC reaches it's maximum level for example 6 VDC, the output of the Op-Amp with again of 2 has never exceeded 9 VDC due to saturation voltages and nonlinearity, so the solution was to use a ± 15 VDC as a saturation limits which was impossible to achieve in the presence of one 12 VDC battery, so it was a must to find other solutions for generating analog output from the PIC.

PIC has the feature of generating pulse with different duty cycles using the PWM (Pulse Width Modulation) pins built in one of its I/O ports, as shown in fig (4.24) the duty cycle of a pulse can be modulated to be within (0 to 100 %), if for example it is 20 % then the pulse is on or logic one for a time forms 20 percent of the total period or pulse time, the idea then is that the average output is the same as duty cycle, more about PWM in PIC is shown in appendix (E).

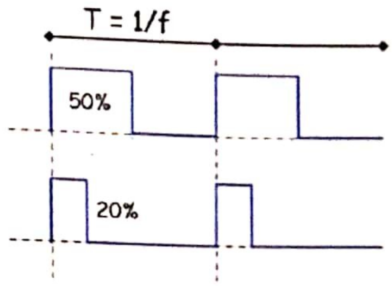


Fig 4.24 PWM and duty cycle

Talking about the PWM without taking about H-bridge circuit is useless, the H-bridge is the circuit needed to translate this modulated pulse into analog signal the actuators understand.

The H Bridge is a logic circuit that is used to control the direction of a motor as shown in fig (4.25).

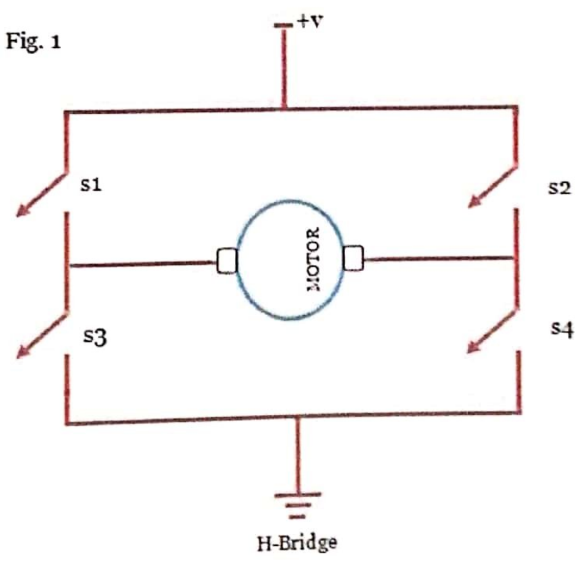
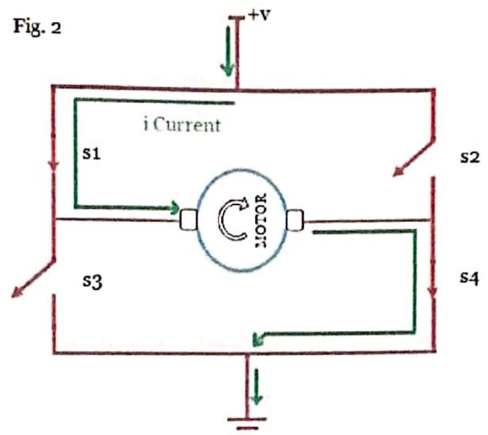


Fig 4.25 H-Bridge simple diagram

The motion needs to close and open switches in order for the motor to rotate in either direction, as shown in fig (4.26) to rotate the motor clockwise, S1 and S4 must be closed while S2 and S3 must be kept open.

Fig. 2

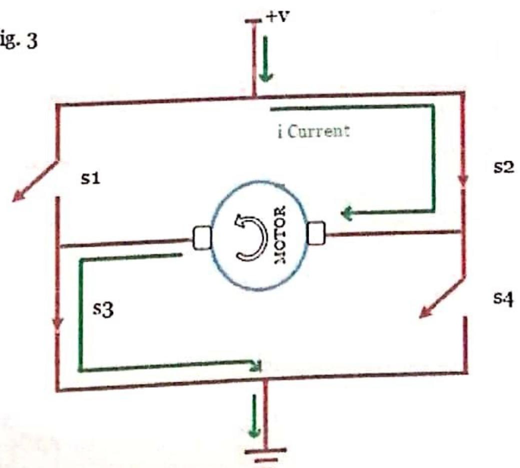


H-Bridge Motor Clockwise Rotation

Fig 4.26 motor rotation with H-bridge

While the opposite is applied to turn the motor to counter clock wise as shown in fig (4.27).

Fig. 3



H-Bridge Motor Anti-clockwise Rotation

Fig 4.27 motor opposite rotation with H-bridge

L298 shown in fig (4.28) is a high current up to 4 Ampere, high voltage up to 46 VDC dual full-bridge driver designed to accept TTL (square wave of logic 1 (5VDC)) logic levels and drive inductive loads such as relays, solenoids, DC and stepping motors, more details are described in appendix (F).

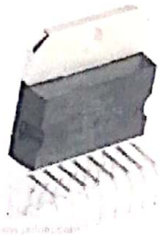


Fig 4.28 L298 dual full H-bridge

Fig (4.29) shows the internal block diagram of L298, as shown it has 4 outputs (pins 1,2) and (pins 3,4) each pair is connected to a motor, in addition each output pair is controlled by three logic pins In 1, In 2 and En A for the first motor (the first pair of outputs) and pins In 3,In 4 and En B for the second motor, so for any motor if the En port is enabled and one of the (In)s is on and the other is off the motor will rotate in a direction while if the (In)s logic is inverted it will rotate in the opposite direction.

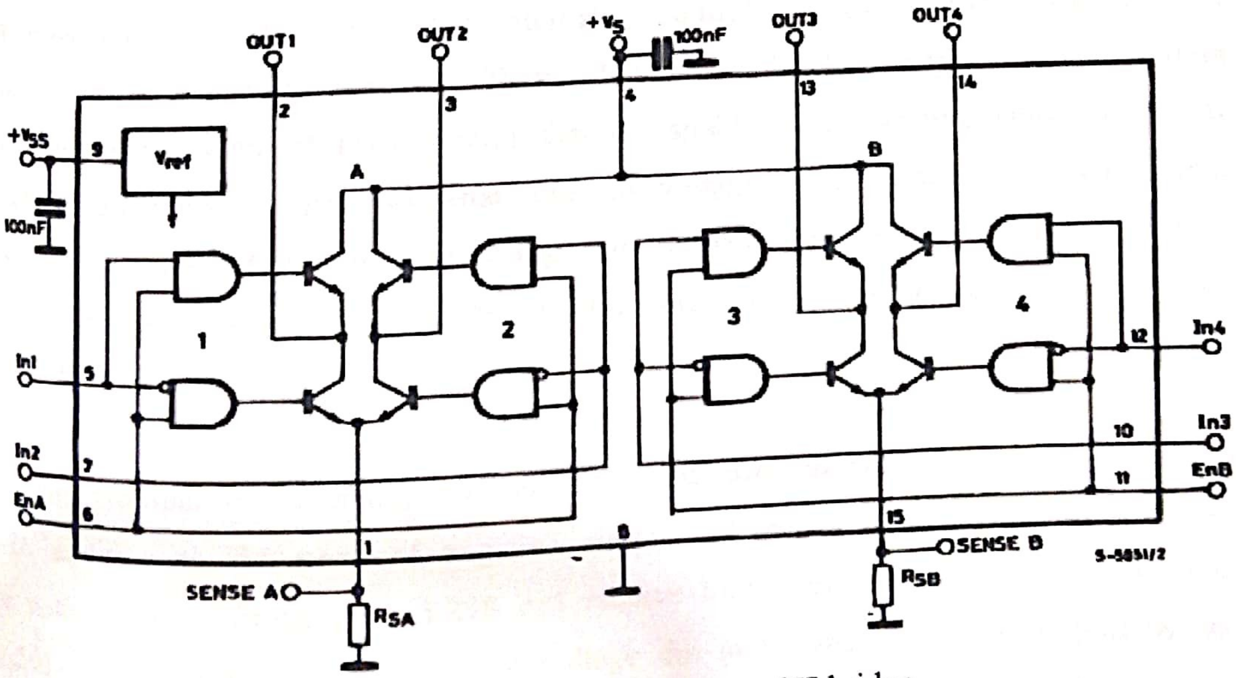
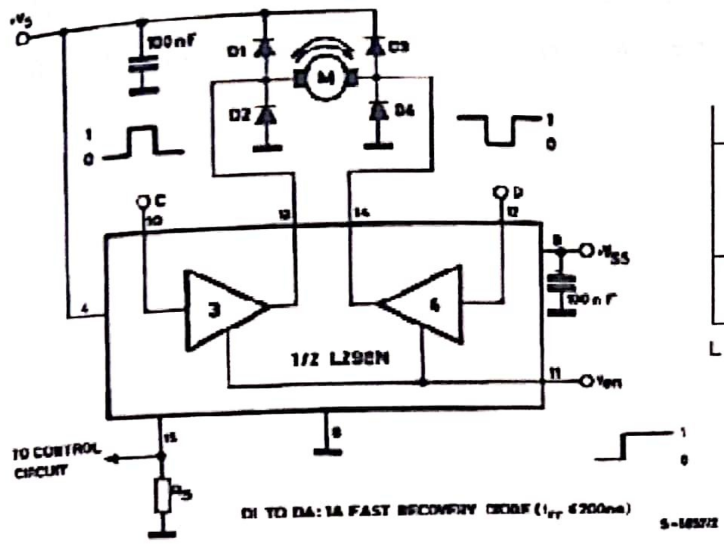


Fig 4.29 internal circuit diagram of H-bridge

The complete truth table for any motor pins is shown in fig (4.30), where the diodes are used to protect the motor from any short circuit could occur.



Inputs		Function
V_{en} - H	C - H, D - L	Forward
	C = L ; D = H	Reverse
	C = D	Fast Motor Stop
V_{en} = L	C = X ; D = X	Free Running Motor Stop

L - Low   H - High   X - Don't care

Fig 4.30 truth table of input ports of H-bridge

Using H-bridge is not only important to receive PWM output from the PIC, but also because it is fit to the motion process required for the system, PIC has only two PWM pins each can be modulated internally, controlling two motors each for two direction and each direction with different duty cycle (analog output and so voltage level) needs some kind of logic circuit that is capable of controlling which motor to use, which direction to turn and what level of voltage needed each time, here PWM pins will be connected to both inputs logic in the H-bridge and the control of which motor to turn on at a time is done by enabling the En port using the software written inside the PIC.

The problem of reversing the direction that was encountered when DAC was used in addition to the need of negative supply voltage is completely solved in H-bridge with PWM technique, the L298 can receive high voltage supply (pin 4 (Vss) in fig (4.29)) up to 46 V, and the level of voltage the motor receives is controlled by the duty cycle of the pulse generated by the PIC, the direction of rotation is handled by which PWM pin is enabled.

4.3 Electrical Implementation

After describing the electrical and electronic components to be used, the implementation of the electrical design is shown in fig (4.31) and fig (4.32).

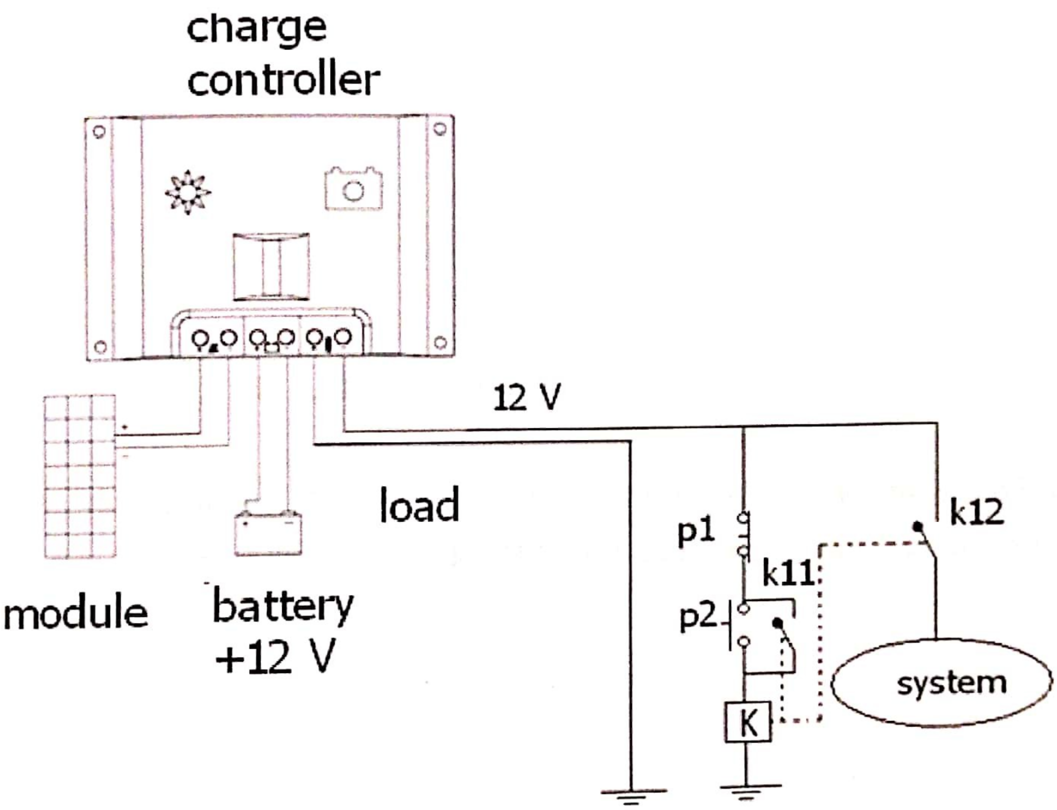


Fig 4.31 electrical system connection

Where $P1$ is normally closed push button for turning off the whole system, to turn it on $P2$ is used, a relay is used also to control the process of turning the system on and off, where $k11$is a NO (normally open) switch in the relay used for self holding to keep the system on after removing hand of the button$P2$, while $K12$ is the switch responsible for providing the supply to the rest of the system, where $k11$ and $k12$ depends on the state of the relay K1.

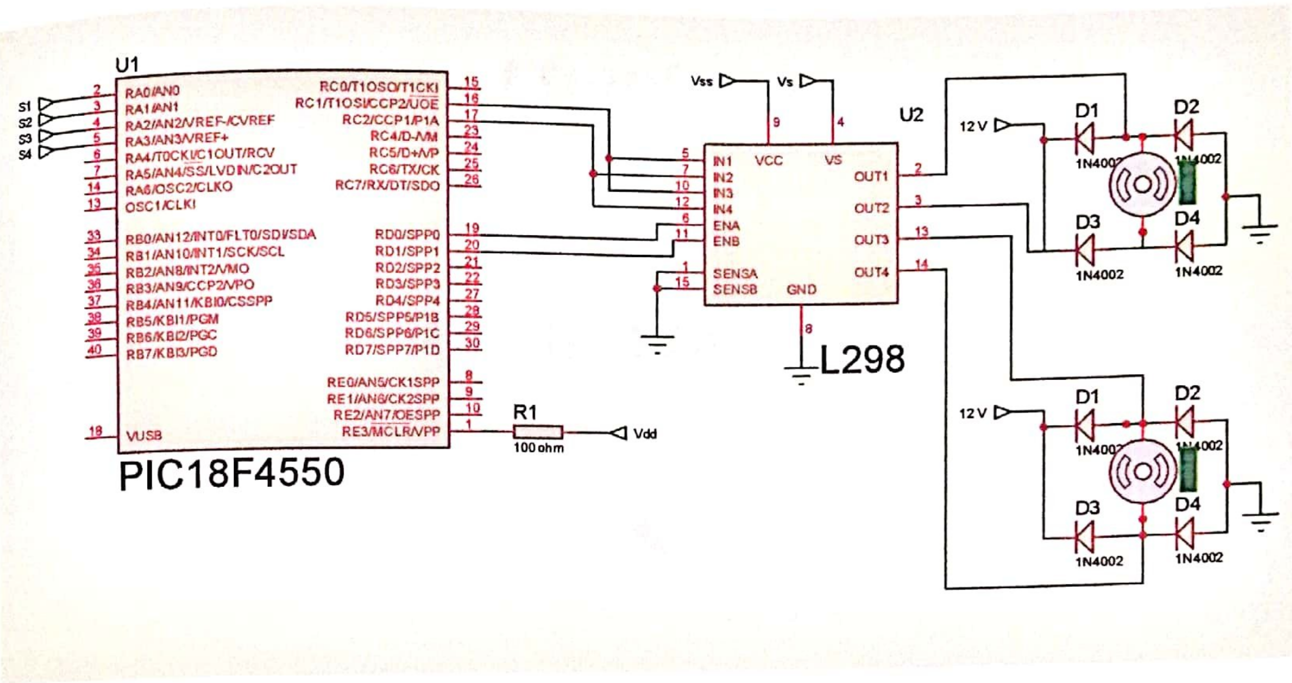


Fig 4.32 control system connection

While fig (4.32) shows the internal implementation of the electronic and control system, where the PIC is connected to the H-bridge after which the two motors to be controlled is connected.

Chapter 5

Control Design

&

Implementation

5.1. General Outlook

The control of the panel's position is done through the control law that compares between the output voltages of the sensors which vary due to the change in sun's position as shown in fig (5.1); this variation will be used to drive the system to the required position again.

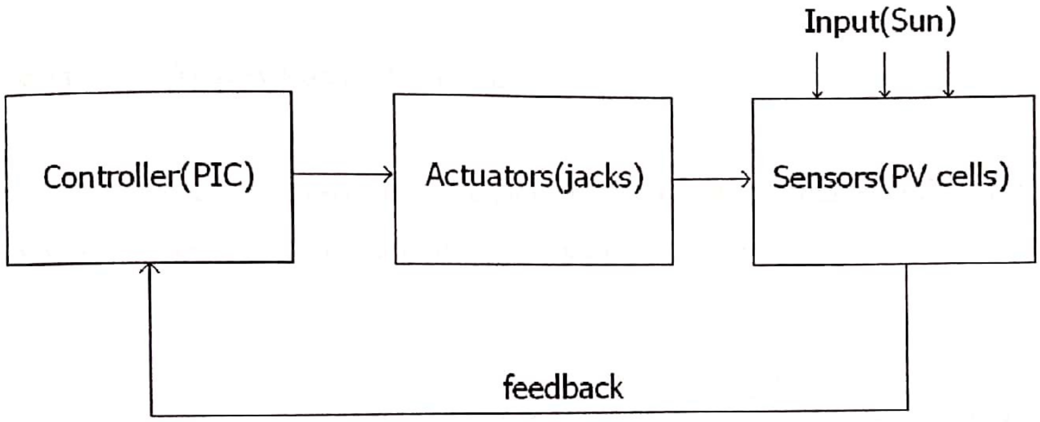


Fig 5.1 general block diagram

Sensors will lead the system to the position where the panel faces the sun again, after comparing their output voltages; one sensor will have more voltage if it receives more light intensity than the other due to the orientation of each sensor and the continuous variation of sun's position.

Feed back of sensors output will be used by the controller that will be programmed in PIC to control the motion of the jacks in order to keep those transducers with equal voltages under sun light as a result keeping the panel in its maximum power position.

Mathematical modeling, block diagrams, simulation, controller design and PIC programming will be shown next.

5.2 Mathematical modeling and block diagram

The mathematical modeling of the system is implemented by modeling the mechanical and electrical components in addition to the sensors used; the goal is to model the system such that the input voltage to the motor of the jack is converted to rotational motion (angle) for the panel a around the Z axis or for the U-part around the Y axis as follows.

5.2.1 Electrical Analysis and Modeling

The electrical analysis of the dc jacks is related to the analysis of the internal dc motor where its model in s-domain is shown in fig (5.2)

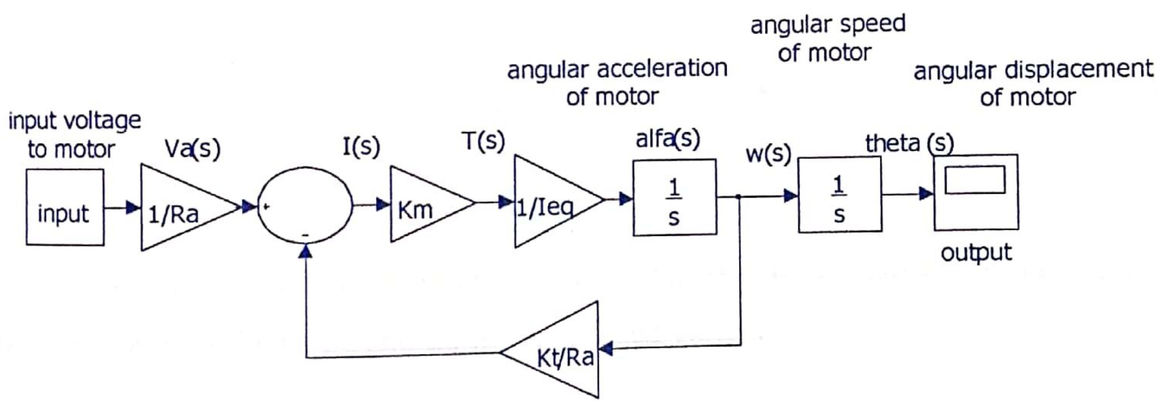


Fig 5.2 motor block diagram

$$T = K_m I_a \qquad 5.1$$

Where T is the torque at motor shaft, K_m is the motor torque constant and I_a is the armature current.

The Laplace transform of this equation is

$$T(s) = K_m I_a(s) \quad 5.2$$

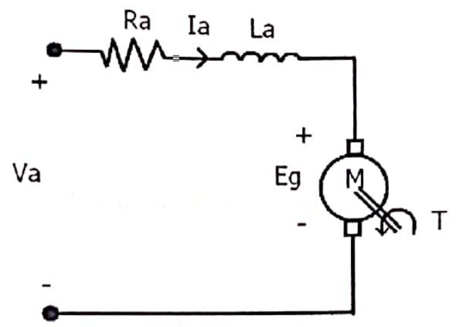


Fig 5.3 electrical analysis of motor

From the electrical circuit shown in fig (5.3)

$$V_a = I_a * R_a + \dot{I_a} * L_a + E_g \quad 5.3$$

Where V_a is the armature voltage, R_a is the armature resistance, L_a is the armature inductance and E_g is the induced voltage.

The Laplace transform of this equation is:

$$V_a(s) = I_a(s)(R_a + sL_a) + E_g(s) \quad 5.4$$

The induced voltage in motor is related to its angular velocity as follows

$$E_g = K_t * w \quad 5.5$$

Where w is the angular velocity of the motor and K_t is the back electromotive force constant.

The Laplace transform of this equation is:

$$E_g(s) = K_t * s\theta(s) \qquad 5.6$$

From eq (5.4) and eq (5.6) it can be shown that:

$$I_a(s) = \frac{V_a(s)}{R_a + sL_a} - \frac{K_t * s\theta(s)}{R_a + sL_a} \qquad 5.7$$

If it is assumed that the armature inductance L_a is small compared to R_a, then eq5.7 becomes

$$I_a(s) = \frac{V_a(s)}{R_a} - \frac{K_t * s\theta(s)}{R_a}$$

In order to figure out the motor constants several tests were done, first the voltage with velocity constant K_t was found, the internal motor speed with the gear system connected was calculated using a tachometer which has a constant relation between it's output voltage and the velocity of it's shaft, it produces 36 V for a 3750 rpm, when the motor of the jack was connected to the generator shaft it produces 940 mV for a 30 V armature voltage, as shown in fig (5.4) an oscilloscope was used to show the voltage and speed relation of the tachometer .

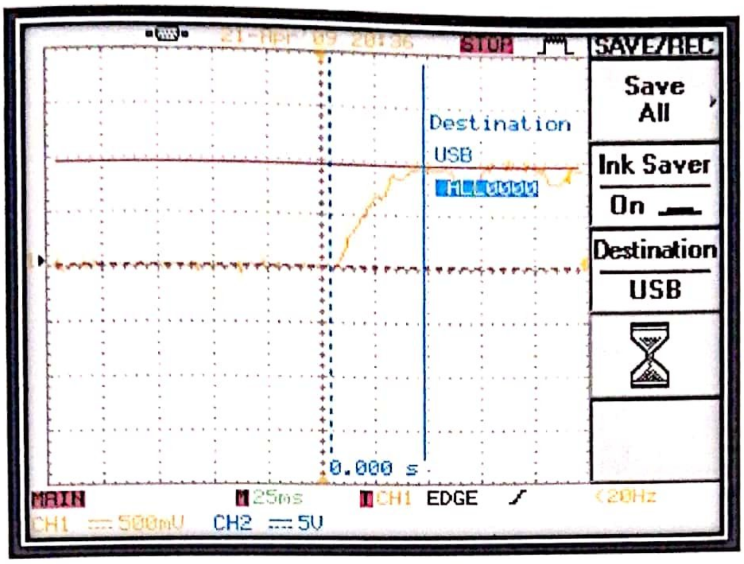


Fig 5.4 oscilloscope output figure

$$\omega_{motor} = 0.94 * \left(\frac{3570}{36}\right) * \frac{2\pi}{60} = 9.75\ rad/s$$

To find K_t the induced voltage must be found, for the previous motor speed the armature voltage $V_a = 30$ V, the motor internal resistance $R_a = 5.6\ \Omega$ and the armature current $I_a = 0.39$ A, for these values

$$E_g = V_a - I_a R_a \qquad 5.8$$

$$E_g = 30 - 0.39 * 5.6$$

$$E_g = 27.81\ V$$

Then the electromagnetic constant of the actuator K_t is calculated according to eq5.5

$$E_g = K_t * \omega$$

$$K_t = \frac{E_g}{\omega}$$

$$K_t = \frac{27.81}{9.75} = 2.8\, V.s/rad$$

In order to find torque/current constant the torque produced for the previous armature voltage was found where the efficiency of the actuator is η=0.85 then

$$P_{in} = \frac{P_{out}}{\eta} \tag{5.9}$$

Substituting for P_{in} and P_{out} yields

$$V_a I_a = \frac{T\omega}{\eta}$$

$$30 * 0.39 = \frac{T * 9.75}{0.85}$$

$$T = 1.02\ N.m$$

Back to eq 5.1 the electromechanical constant K_m is calculated through the following equation

$$K_m = \frac{T}{I_a}$$

$$K_m = \frac{1.02}{0.39} = 2.61\ N.m/A$$

5.2.2 Mechanical Analysis and Modeling

From the mechanical analysis

$$T = I_{eq} * \ddot{\theta} \quad 5.10$$

Where I_{eq} is the equivalent mass moment of inertia at motor shaft and $\ddot{\theta}$ is the angular acceleration of the motor.

The Laplace transform of this equation is

$$T(s) = s^2 I_{eq} * \theta(s) \quad 5.11$$

In order to find out the equivalent moment of inertia on motor shaft, the energy equation will be used such that all moving parts of different velocities will be included as shown next, where for the first jack.

$$\frac{1}{2} J_{eq\ lower\ jack}\ \dot{\theta}^2_{lower\ motor} = \frac{1}{2} m_{screw}\ v^2_{screw} + \frac{1}{2} J_{panel\ average\ (Z)}\ \dot{\theta}^2_{panel(Z)} \quad 5.12$$

Where $J_{eq\ lower\ jack}$ is the equivalent mass moment of inertia on the internal lower motor shaft, $\dot{\theta}_{lower\ motor}$ is the angular velocity of the internal lower motor, m_{screw} is the mass of the screw gear, v_{screw} is the linear velocity of the screw gear, $J_{panel\ average\ (Z)}$ is the average inertia of panel around Z axis and $\dot{\theta}_{panel(Z)}$ is the panel angular velocity around the Z axis.

Simplifying eq5.12 leads to

$$J_{eq\ lower\ jack} = m_{screw}\left(\frac{v_{screw}}{\dot{\theta}_{lower\ motor}}\right)^2 + J_{panel\ average\ (Z)}\left(\frac{\dot{\theta}_{panel(Z)}}{\dot{\theta}_{lower\ motor}}\right)^2$$

Let $C_{motor/jack} = \left(\frac{v_{screw}}{\dot{\theta}_{lower\ motor}}\right)$ be a constant that relates the motor and jack motions either their velocities or their displacements, and let $C_{L.jack/panel(z)} = \left(\frac{\dot{\theta}_{panel(Z)}}{v_{screw}}\right)$ be a constant that relates the lower jack and the panel motions around the Z axis as shown in fig (5.5), then

$$C_{motor/panel(z)} = \frac{\dot{\theta}_{panel(Z)}}{\dot{\theta}_{lower\ motor}} = C_{motor/jack} * C_{L.jack/panel(z)} \qquad 5.13$$

Where $C_{motor/panel(z)}$ is the constant that relates the motion of the motor of the lower jack and the panel around the Z axis.

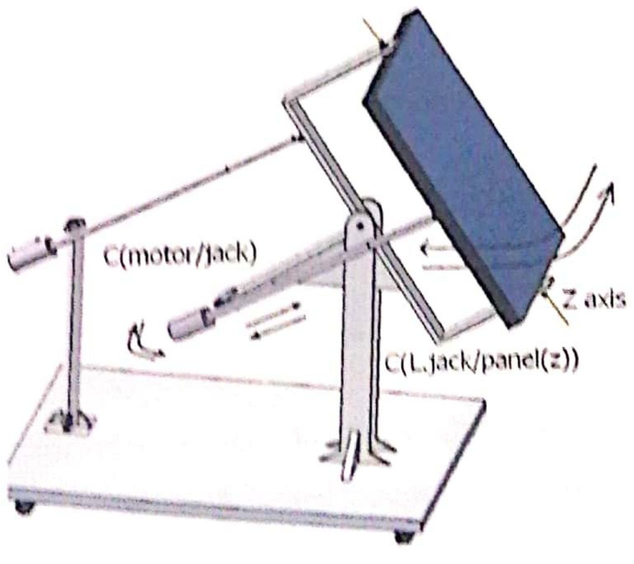


Fig 5.5 motion constants

Then eq5.12 becomes

$$J_{eq\ lower\ jack} = m_{screw}\left(C_{motor/jack}\right)^2 + J_{panel\ average\ (Z)}\left(C_{motor/panel(z)}\right)^2$$

In order to find $C_{motor/jack}$ two experiments have been done, first the jack linear speed has been measured for a 30 V armature voltage as a result the jack length increased from 18.4 mm to 34.2 mm through 30s and so

$$v_{screw} = \frac{\Delta X}{\Delta t} \qquad 5.14$$

$$v_{screw} = \frac{(34.2 - 18.4) * 10^{-2}}{30 - 0}$$

$$v_{screw} = 5.26\ mm/s$$

But

$$v_{screw} = C_{motor/jack}\ \omega_{motor}$$

$$C_{motor/jack} = \frac{v_{screw}}{\omega_{motor}}$$

$$C_{motor/jack} = \frac{5.26 * 10^{-3} m/s}{9.75\ rad/s}$$

$$C_{motor/jack} = 5.4 * 10^{-4} m/rad$$

The second includes testing the linear displacement of the screw for each complete round where each round cause the screw to extend by a 3.5 mm, and so

$$C_{motor/jack} = \frac{linear\ displacement}{revolution} \qquad 5.15$$

$$C_{motor/jack} = \frac{0.0035}{2\pi} = 5.57 * 10^{-4}\ m/rad$$

A value of $C_{motor/jack} = 5.5 * 10^{-4} m/rad$ is taken to be the average of the two results of the tests, this value is valid for the two jacks of the system as the same jack size with the same level of voltage is used for both motions.

For $C_{L.jack/\ panel(z)}$ the average value of it was experimentally founded to be 300 deg/m (3 deg/cm extension) for the lower jack, such that the panel rotates about 3 degrees for each 1 cm extension by the jack.

Back to eq5.12 the mass of the screw in addition to the average value of panel's inertia around the Z axis still not found, the mass of the screw was found to be about 2.5 Kg while the average value of the panel inertia around Z axis is calculated in the mechanical chapter and will be used here where $J_{panel\ average\ (Z)} = 0.2\ kg.m^2$, for eq5.12 the equivalent inertia on motor shaft can now be found

$$J_{eq\ lower\ jack} = 2.5 * (5.5 * 10^{-4})^2 + 0.2 * (300 * 5.5 * 10^{-4})^2 = 5.44 * 10^{-3}$$

$$J_{eq\ lower\ jack} = 0.00544\ kg.m^2$$

For the upper jack the same screw mass in addition to the motor jack constant will be used, while the (upper jack / U part) constant was found to be 280 deg/m (2.8 deg/cm extension) such that the U part rotates by a 2.8 degrees for each 1 cm extension by the upper jack, the average value of the panel inertia around Y axis in addition to the U part and the lower jack was found in mechanical chapter to be 1.43 $kg.m^2$ and so

$$J_{eq\ upper\ jack} = m_{screw}\left(C_{motor/jack}\right)^2 + J_{ave\ (Y)}\left(C_{motor/U.part\ (Y)}\right)^2 \qquad 5.16$$

$$J_{eq\ upperjack} = m_{screw}\left(C_{motor/jack}\right)^2 + J_{ave(Y)}\left(C_{upper\ jack/Upart} * C_{motor/jack}\right)^2$$

$$J_{eq\ upper\ jack} = 2.5 * (5.5 * 10^{-4})^2 + 1.43 * (280 * 5.5 * 10^{-4})^2$$

$$J_{eq\ upper.\ jack} = 0.0339\ kg.m^2$$

As a summary the mechanical and electrical constants that were found are as follows

$$Ra = 5.6\ \Omega$$

$$km = 2.61\ N.m/A$$

$$K_t = 2.8\ V.s/rad$$

$$C_{motor/jack} = 5.5 * 10^{-4} m/rad$$

$$C_{L.jack/\ panel(z)} = 300\ deg/m$$

$$C_{upper\ jack/Upart} = 280\ deg/m$$

$$J_{eq\ lower\ jack} = 0.00544\ kg.m^2$$

$$J_{eq\ upper\ jack} = 0.0339\ kg.m^2$$

Now the block diagram for each motor can be found then, this block diagram will be extended to include the motion constants that convert the motor rotation into panel rotation around the different axes.

The block diagram of the first motor is shown in fig (5.6)

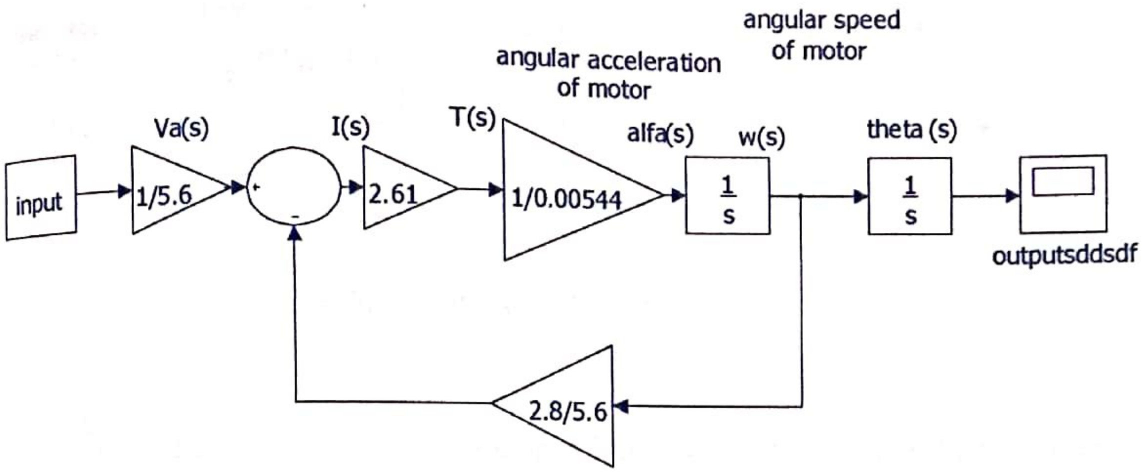


Fig 5.6 first motor block diagram

After reduction and simplification this diagram can be as shown in fig (5.7)

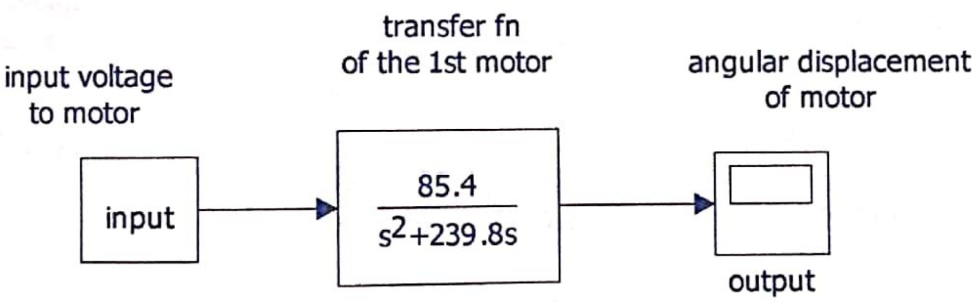


Fig 5.7 first motor reduced block diagram

Now in order to have the transfer function that relates the input voltage to the jack (motor) with the output angular displacement of the panel which is the desired value to be controlled, the constants that relates motor rotation with jack linear motion in addition to the panel rotation should be included in the block diagram as shown in fig (5.8).

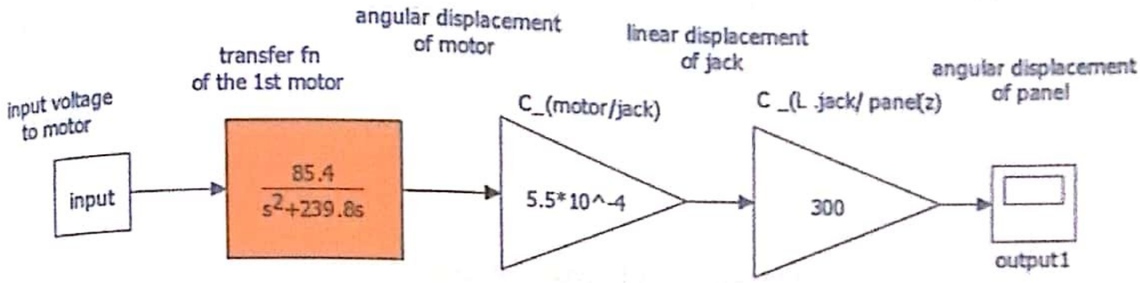


Fig 5.8 lower jack block diagram

As result of these constants the open loop transfer function of the first motion around the Z axis that includes the jack and the panel that rotates is as shown in fig (5.9).

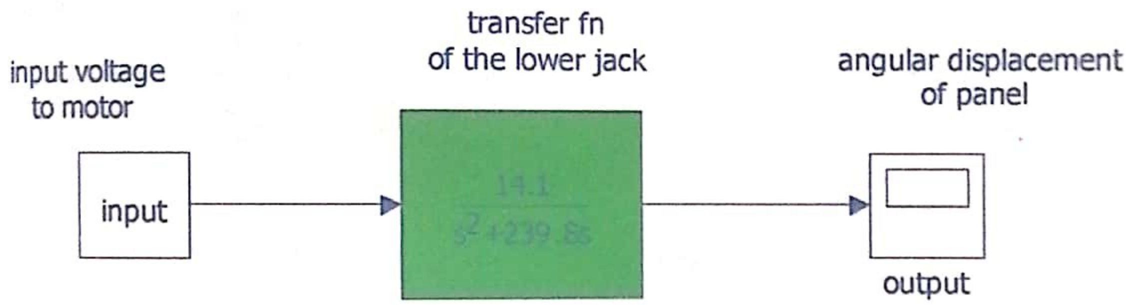


Fig 5.9 reduced lower jack block diagram

The block diagram of the 2nd motor is shown in fig (5.10), the only difference between it and the one shown in fig (5.6) is the equivalent inertia the motor has to overcome to complete the required motion.

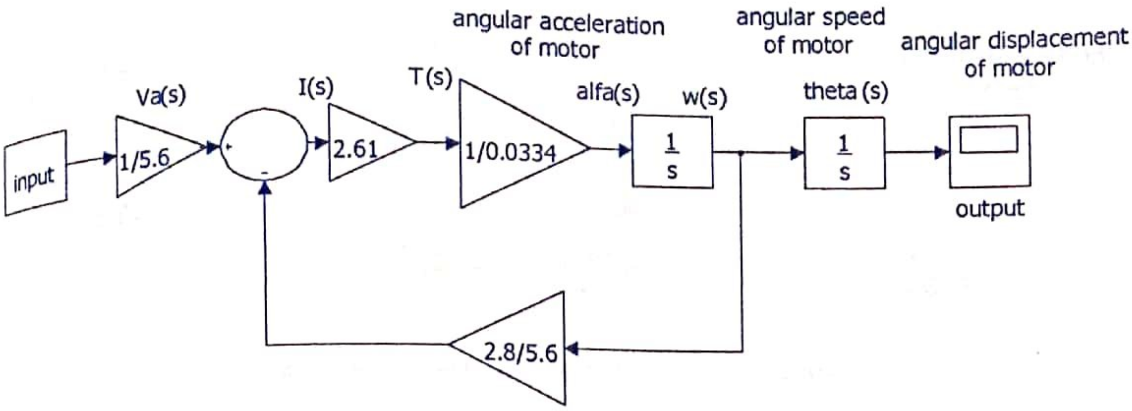


Fig 5.10 second motor block diagram

Simplification and insertion of motion constants that relates angular displacement of motor with that of the U-part around the Y axis leads to the simplified block diagram shown in fig (5.11)

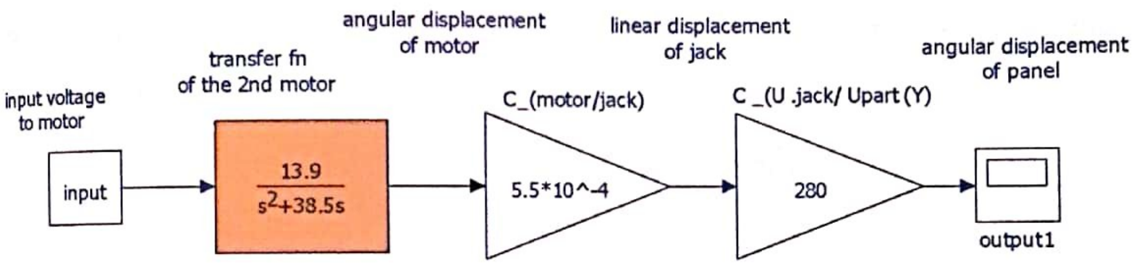


Fig 5.11 upper jack block diagram

And finally the open loop transfer function of the upper jack including the inertia it moves around the Y axis is shown in the reduced block diagram fig (5.12).

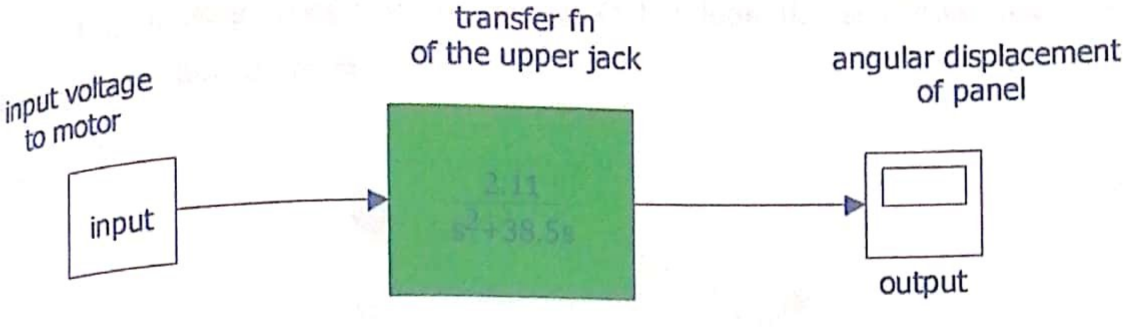


Fig 5.12 reduced upper jack block diagram

5.2.3 Sensors Analysis

As previously mentioned in the electrical implementation, small PV cells will be used as sensors, in modeling those sensors will be used for feedback signal as shown in fig (5.13) housing of aluminum is used to cover the sun light from one of the sensors, however the other one is still capable of getting this light, as a result one of them will have more power than the other such that this power difference will lead the actuators motion through the controller.

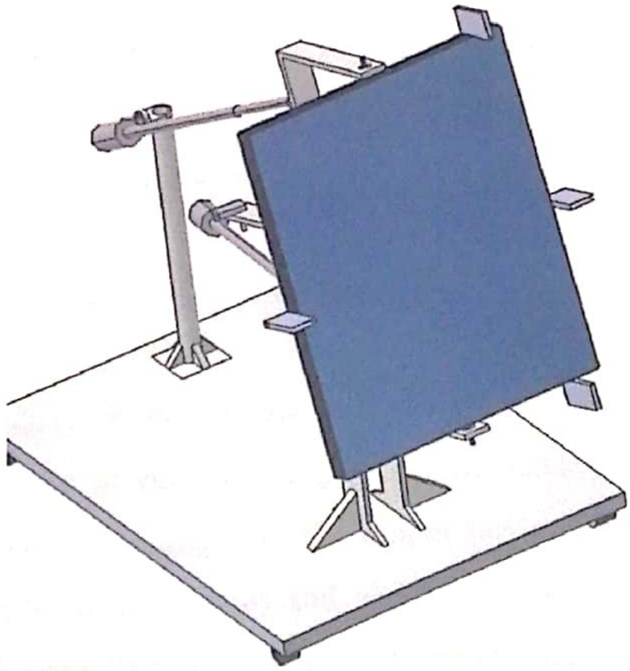


Fig 5.13 sensor Aluminum housing design

The housing design shown in fig (5.14) hide the sun from one cell, but the other is free to get light

Fig 5.14 sensor Aluminum housing

For these sensors, their output powers were assumed to vary with the panel's position, this was right for the sensor that is covered by the housing, however the one that is free to get light didn't show noticeable variation in it's output voltage and so it is considered to have the extra power (voltage) over the covered one and so when their output voltages are compared the error signal will lead the system to the correct position as shown next.

$$P_{out(sensor1)} = P_{in\,(sun)} \quad 5.17$$

$$P_{out(sensor2)} = C_2\theta_{panel} \quad 5.18$$

Where $P_{out(sensor1)}$ is the output power of the sensor that receives more light due to changes in sun path, $P_{in\,(sun)}$ is the extra power this sensor has over the lower one, $P_{out(sensor2)}$ is the output power of the sensor with lower light intensity (the covered one) and so lower output, C_2 is a constant relates its power with the panel's position that is pointed by θ_{panel} .

Tests were made to find the change in the output voltage of each sensor as the panel rotates, Protractor, paper and voltmeter are the tools used to find out these constants, in average all the sensors have approximately the same constant that relates the panel angular position with their output voltage which is found to be $0.03\ V/deg$, which means that each sensor voltage increase by 0.3 V if the panel rotates by 10 degrees, this constant will be used for both block diagrams of the system in order to have the required feedback of the sensor as will be shown in the simulation part.

It is important to mention that the change in sensors occur in their output powers, but what is measured is their output voltages and this signal is taken to the PIC as analog input because their output current is very small and immeasurable.

5.3 Simulation

The block diagram of the system is made in Simulink in Matlab as shown in fig (5.15), the closed loop model includes the motor model that takes it's signal from the controller, the panel's angular position is multiplied by a constant of motion explained previously so that the variation in sensors power is known, this power is then fed back to the input junction to have the error signal.

In fig (5.15) the uncompensated closed loop block diagram of the lower jack motion is shown, where the values of Kp, Kd, and Ki are all zero, the saturation block is used to limit the input to the motor to 12 VDC, the step input represents the difference in voltage of both sensors that one has over the other due to the light received by each, the output signal represents the increase in the voltage output of the sensor that get less light while the

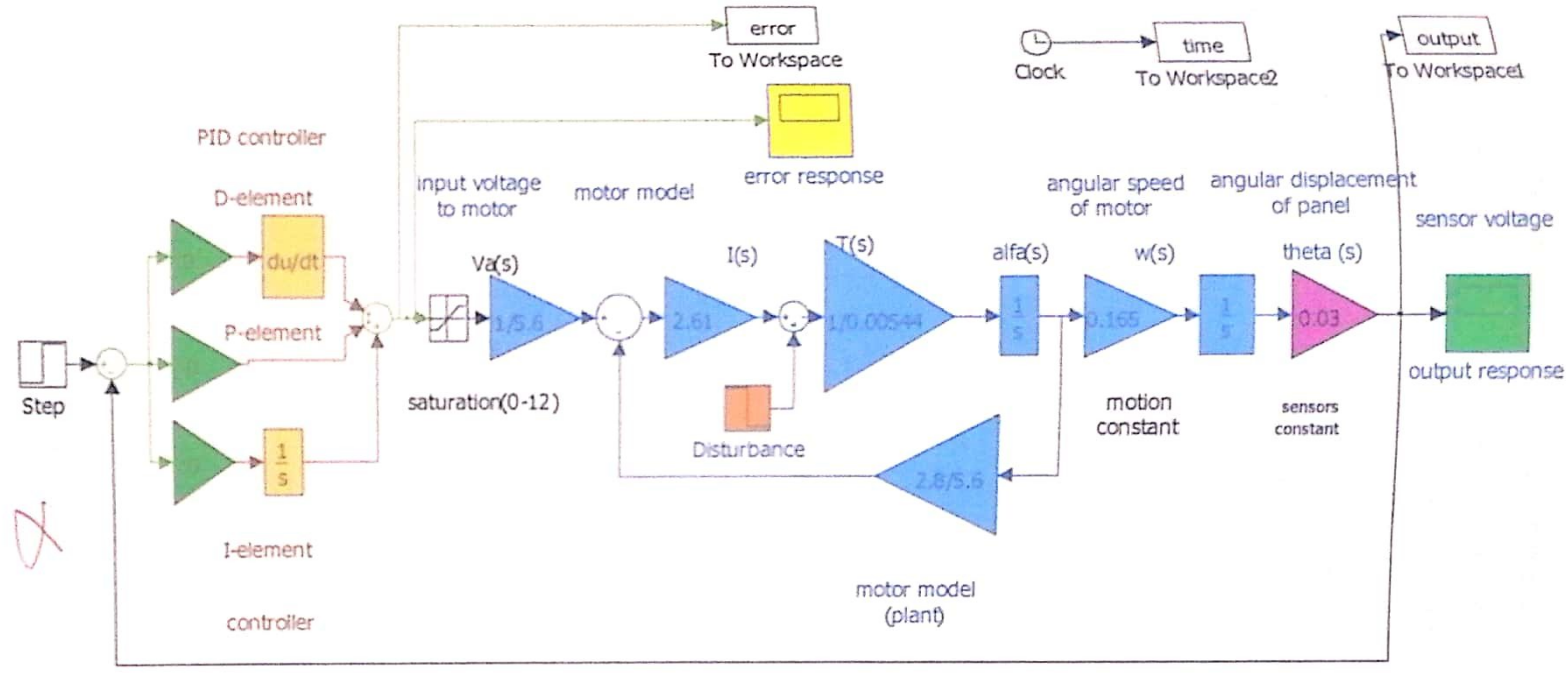


Fig 5.15 uncompensated block diagram of lower jack

Error signal output represents the difference in the sensors' voltages, the disturbance signal represents undesired external effects that might affect or alter the system response and operation like the wind.

The response for both the output and error signals of the uncompensated system is shown in fig (5.16) and fig (5.17) respectively.

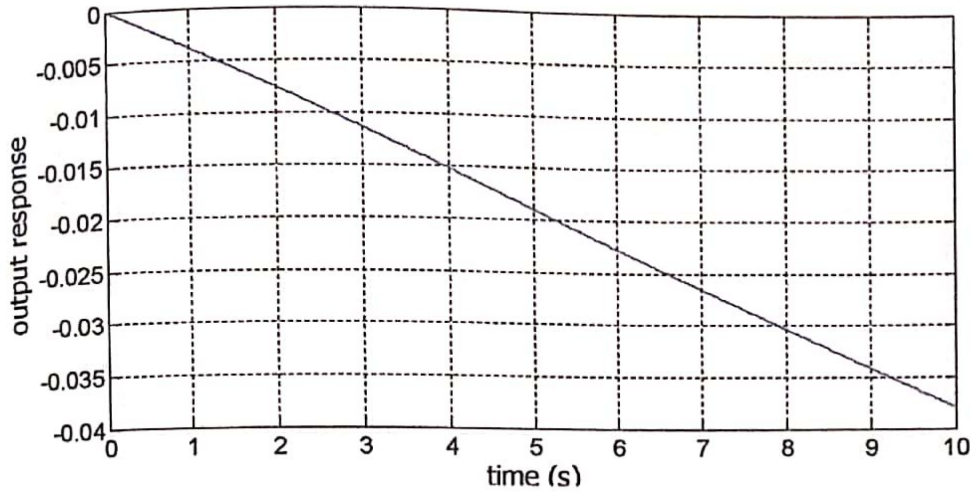


Fig 5.16 response of output signal (uncompensated lower jack block.d)

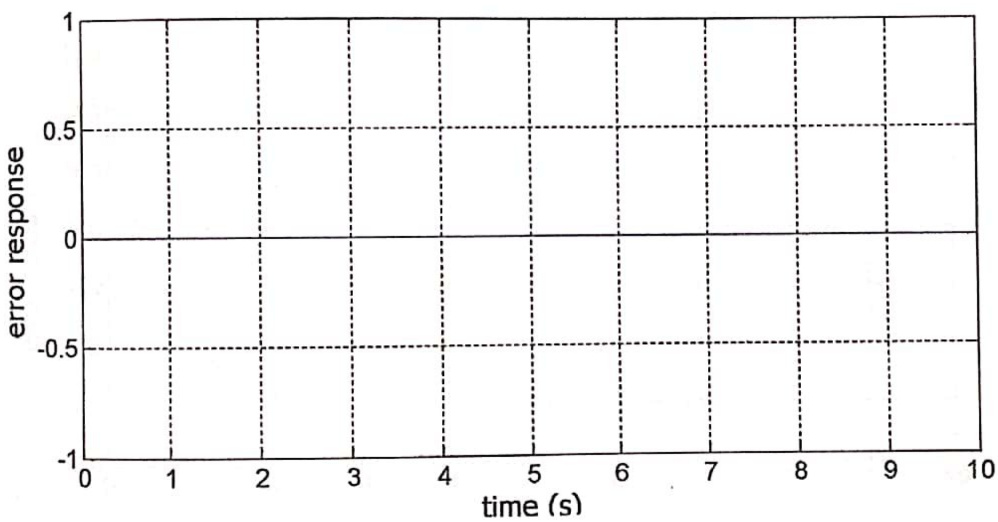


Fig 5.17 response of error signal (uncompensated lower jack block.d)

In order to improve the system response the controller constants must be modified, tuning those parameters lead to the desired response and so for the block diagram of first block with the compensator which is shown in fig (5.18), its response is shown in figs (5.19) and (5.20).

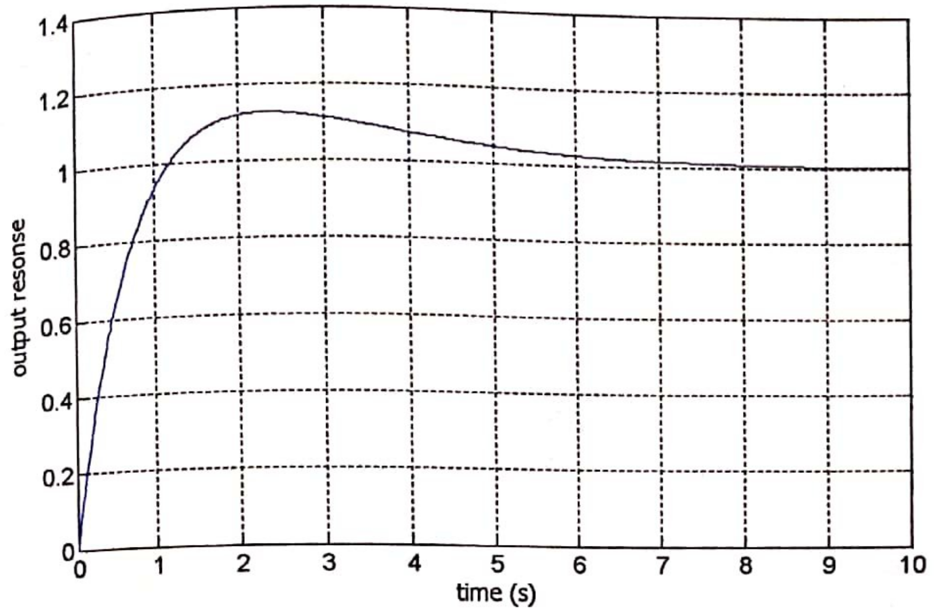


Fig 5.19 response of output signal (compensated lower jack block.d)

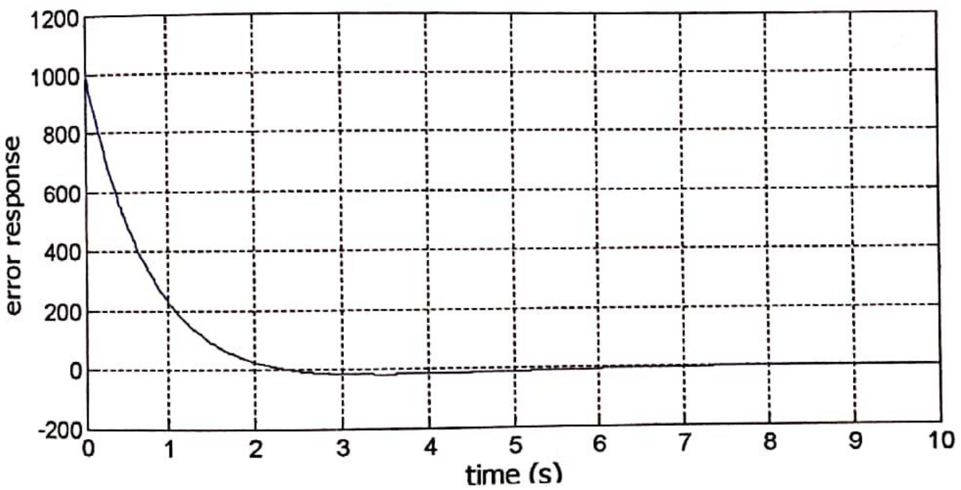


Fig 5.20 response of error signal (compensated lower jack block.d)

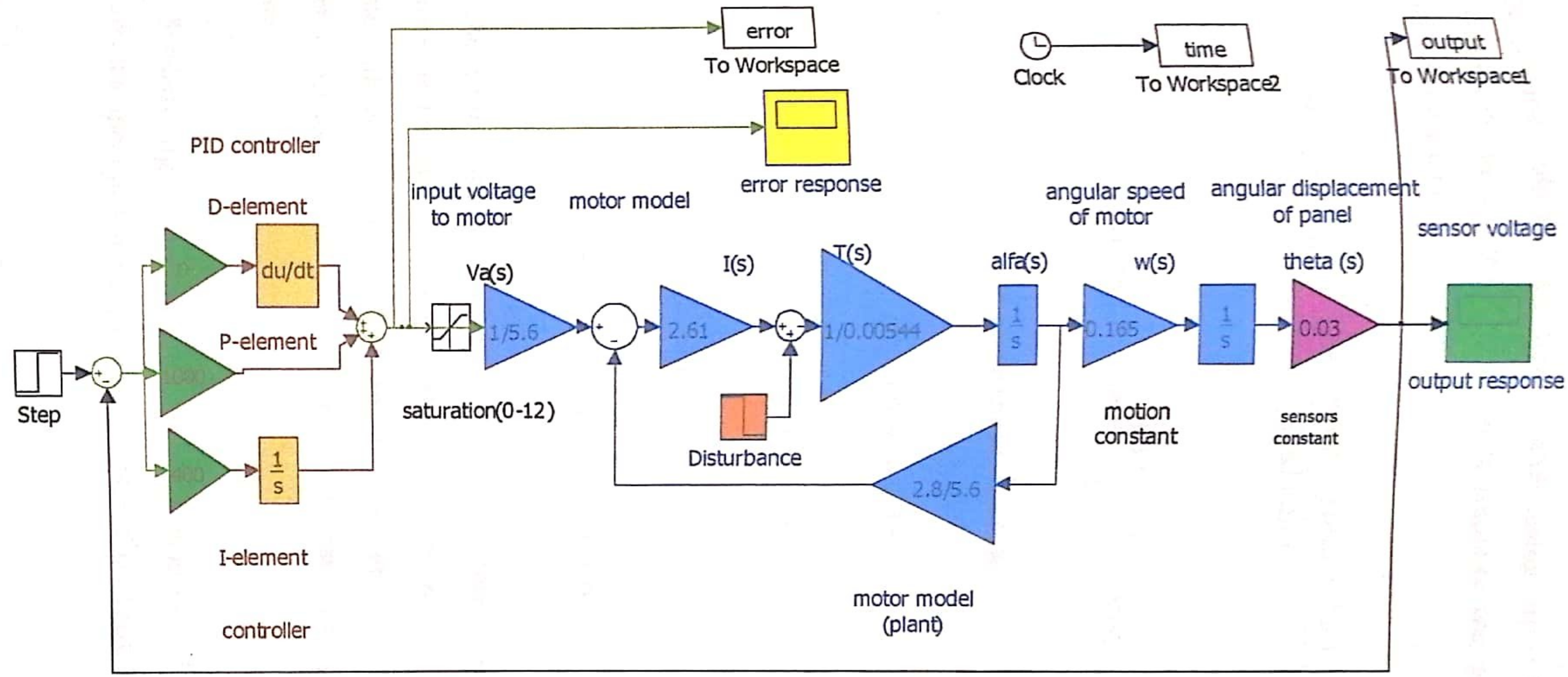


Fig 5.18 compensated block diagram of lower jack

For the previous blocks and figures after using kp = 1000 and ki = 400, with no need for the d element the system response was good from fig (5.19) it has the following transient response

$$\% \, OverShoot = \frac{|max \; value - final \; value|}{final \; value} * 100\%$$

$$\% \, OverShoot \approx \frac{1.126 - 1}{1} * 100\%$$

$$\% \, OverShoot \approx 12.6 \, \%$$

$$Rise \; Time \approx 0.9 \; s$$

$$settling \; time \approx 4 \; s$$

$$Peak \; time \approx 2 \; s$$

$$steady \; state \; error = 0.3 \; \%$$

The error response shown in fig (5.20) shows the difference behavior with time, as the jack moves the light the second sensor receive will increase by time with the first one has an approximate stable output voltage, then the difference between them goes to zero until the system stops at the right position.

Similarly fig (5.21) shows the block diagram of the uncompensated system for the upper jack model, whose response of is shown in fig (5.22)

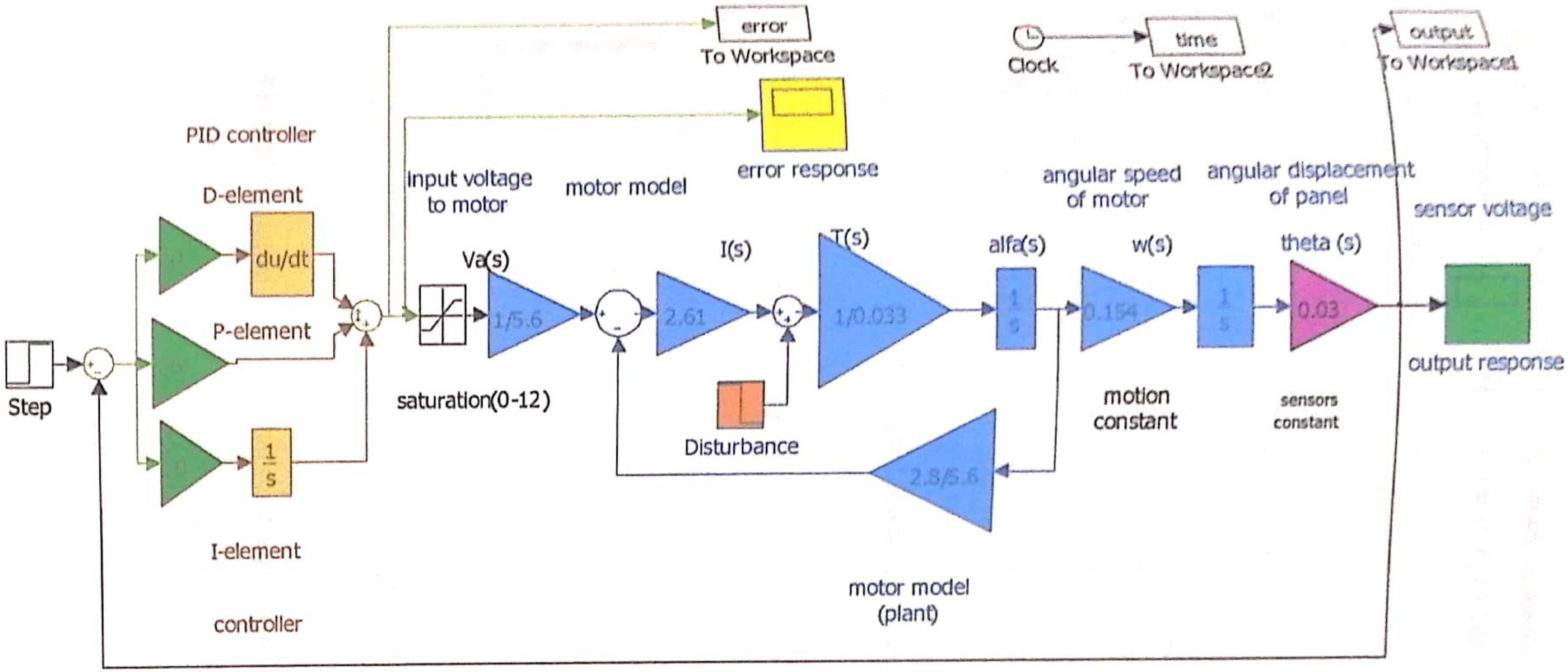


Fig 5.21 uncompensated block diagram of upper jack

and fig (5.23), while the compensated block diagram is shown in fig (5.24) with response diagrams shown in fig (5.25) and fig (5.26).

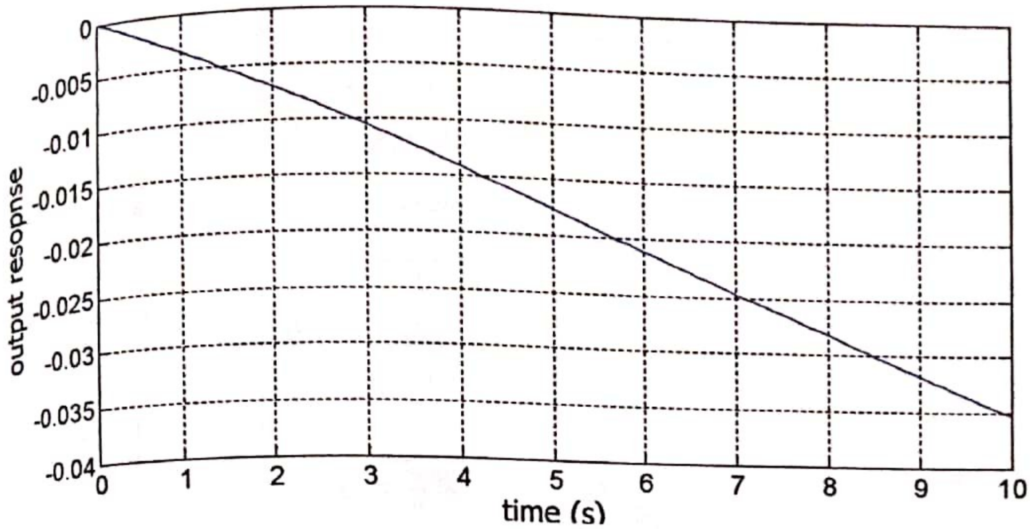


Fig 5.22 response of output signal (uncompensated upper jack block.d)

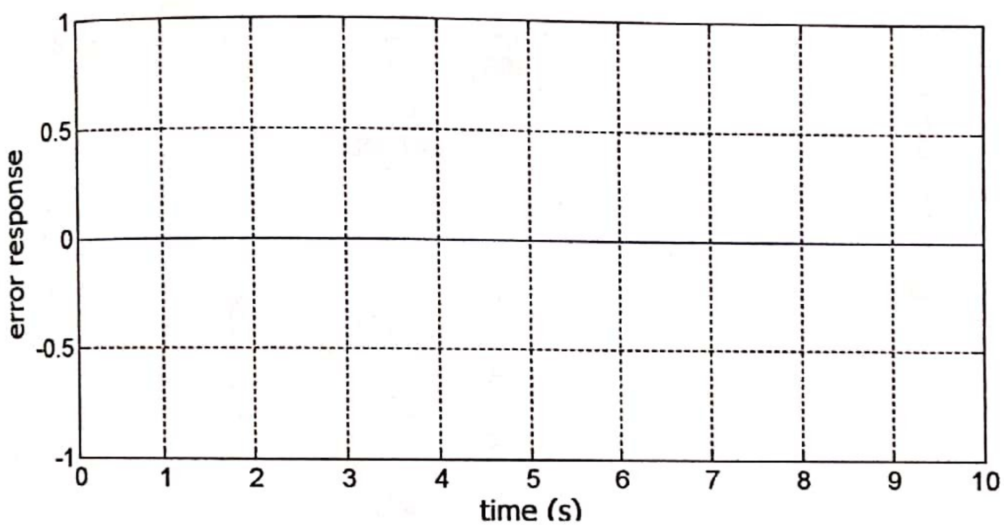


Fig 5.23 response of error signal (uncompensated upper jack block.d)

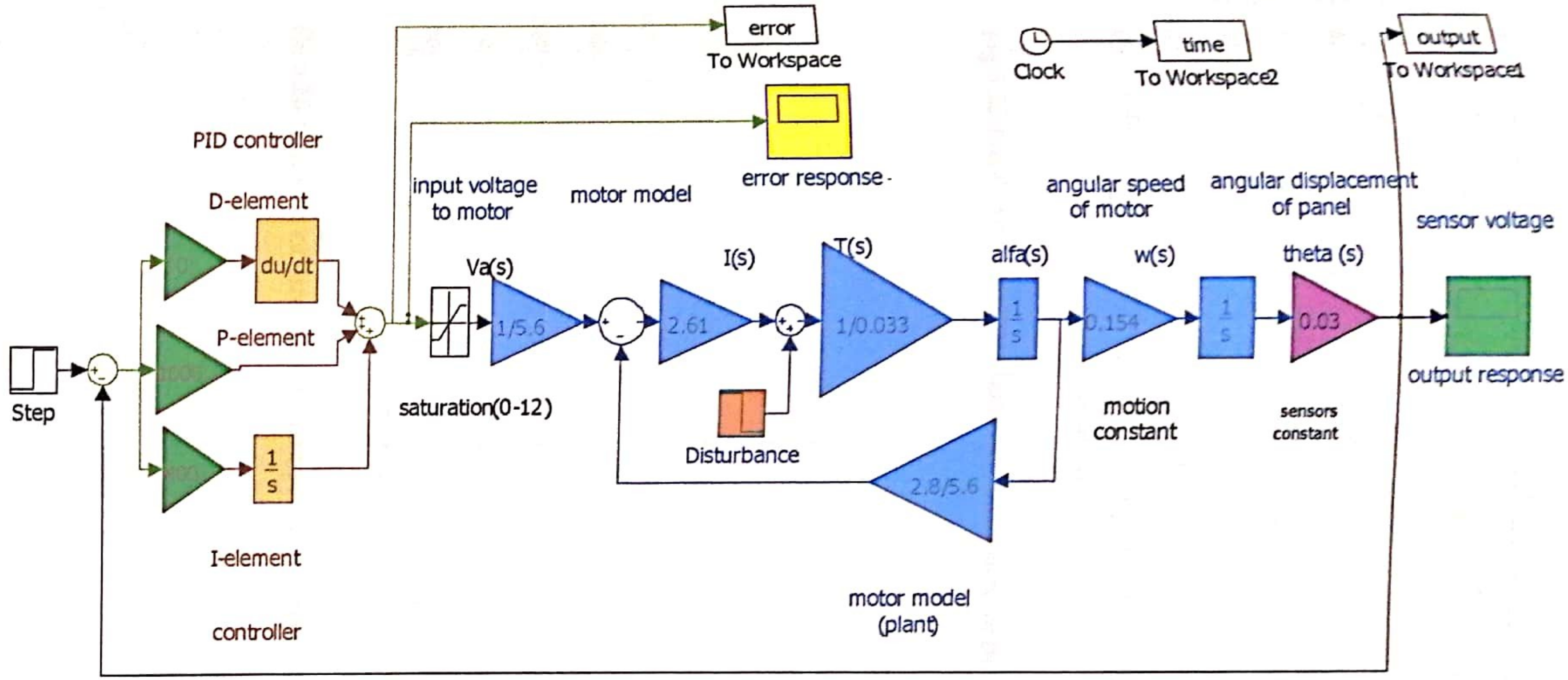


Fig 5.24 compensated block diagram of upper jack

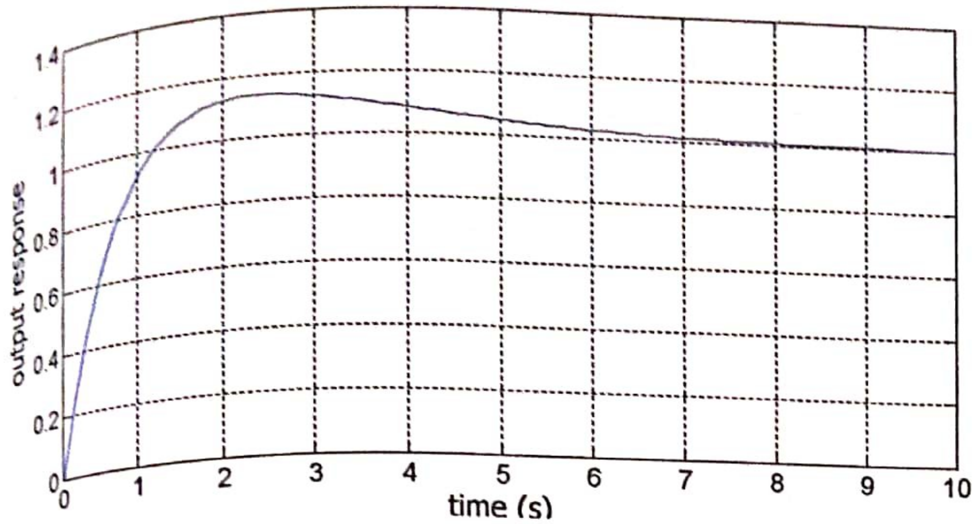


Fig 5.25 response of output signal (compensated upper jack block.d)

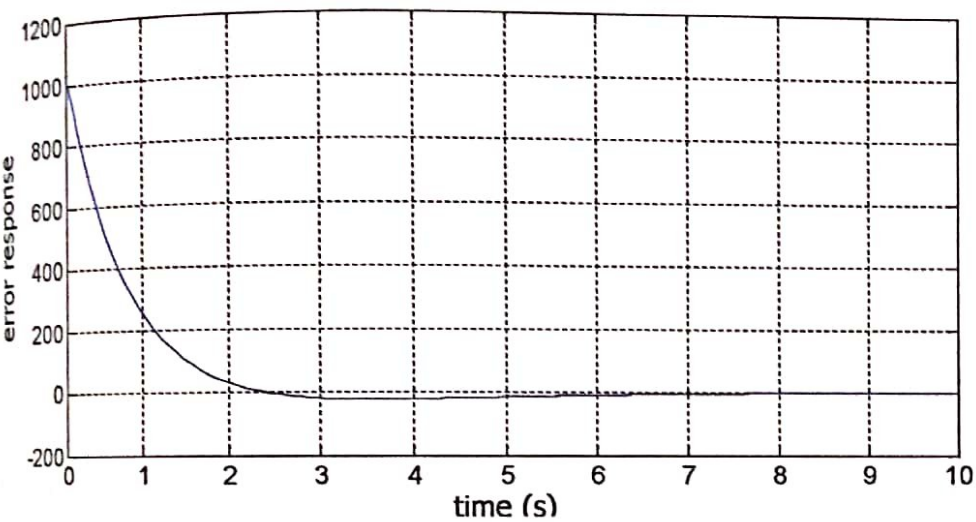


Fig 5.26 response of error signal (compensated upper jack block.d)

The transient response of the upper jack model with controller can be figured out as shown next

$$\% \, OverShoot = \frac{|max\ value - final\ value|}{final\ value} * 100\%$$

$$\% \, OverShoot \approx \frac{1.135 - 1}{1} * 100\%$$

$$\% \, OverShoot \approx 13.5\ \%$$

$$Rise\ Time \approx 0.82\ s$$

$$settling\ time \approx 4.5\ s$$

$$Peak\ time \approx 2.26\ s$$

$$steady\ state\ error = 0.2\ \%$$

5.4 PIC programming

The PIC is device that can be programmed to perform the desired functions by the control unit, it took at least two weeks to learn the basics needed to program the 18f4550 PIC microchip, MPLAB is used to write the code in C language such that it takes the values of the sensors, compare their values, this error signal is then modified through the controller built inside whose values are found in the simulation part of this chapter, after that the pulse modulated signals are sent to the H-bridge with variable duty cycle depending on the error signal, the flowchart of the code that will be written will be shown next in fig (5.27).

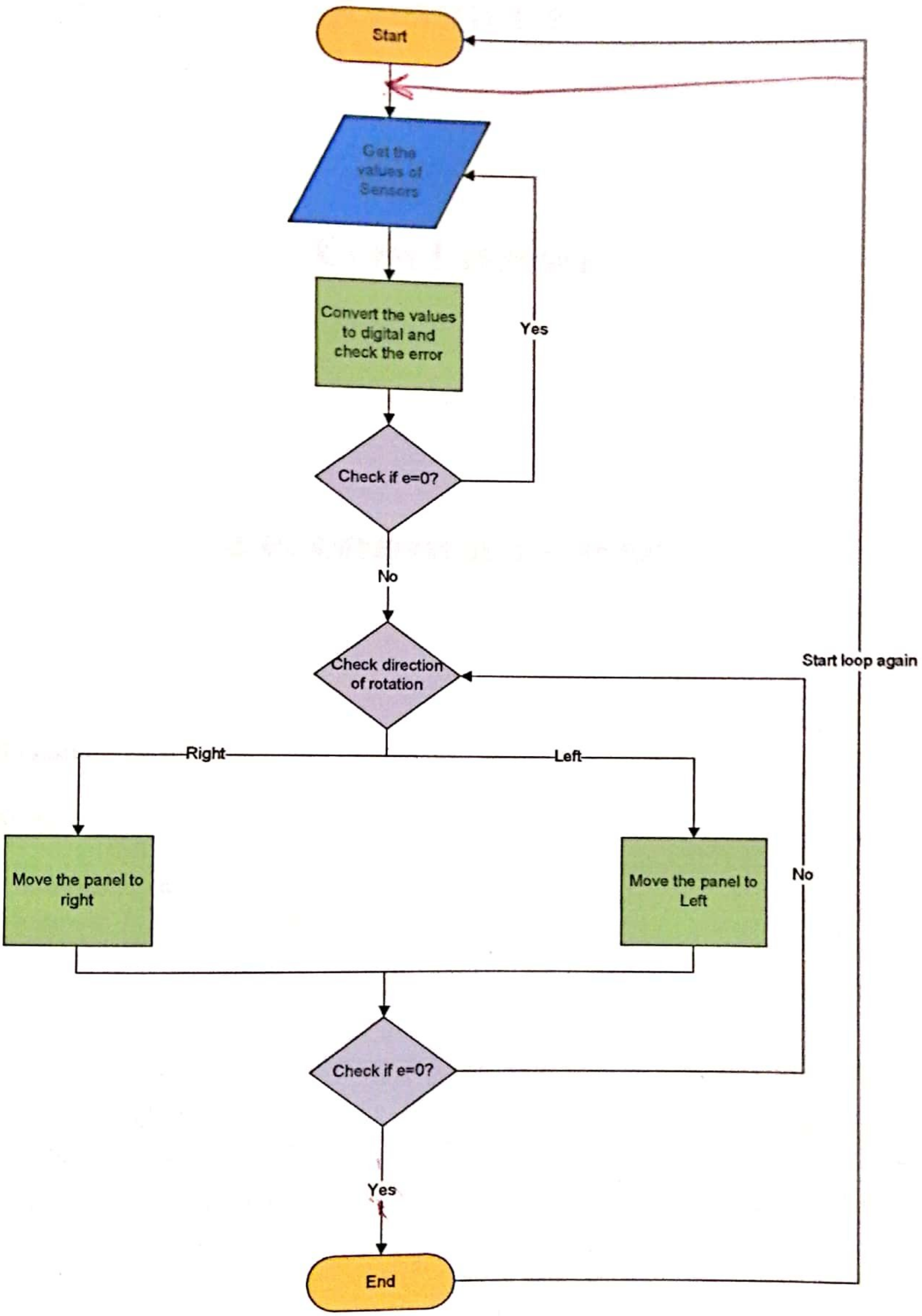


Fig 5.27 flowchart

Chapter 6

Conclusions

&

Recommendations

6.1 Conclusions

6.2 Obstacles

6.3 Recommendations

6.1 Conclusions

The implementation of the project has finished successfully; the solar tracker is able to work as an embedded system such that the microcontroller controls the jacks' motion through the feed back signal coming from sensors with a very good range of motion and durability.

How ever the operation of the system is not perfect, it has encountered some problems due to some errors in the operating program of the PIC microcontroller and the high sensitivity of the values of the sensors due to any disturbance such as wind although they were protected by the housings described earlier.

More efforts are still needed to complete the goals of the solar tracker in order to achieve better and more precise tracking in the two directions, more testing and tuning are to be made to improve its performance specially on the operating program written to the microcontroller and its sensors calibration.

While the performance of the system does need more work, the performance of the solar system is much better, the solar panel is able to charge the battery controlled by the overcharge controller, the battery can handle the motion of the system with approximately no loss of it's capacity, the actuators used drew a very little current and the mechanical structure used made it smooth moveable system with small friction such that the needed torque is moderate.

6.2 Obstacles

As any first time project many problems and obstacles were encountered, technical, economical and uncontrolled barriers made it very hard but not impossible mission to finish the project goal.

A great obstacle stood up against the team when their was a need to change the design of the system due to the expected large friction that might face one of the motors in the old design, this procedure took about 2 to 3 weeks in order to come up with a new and efficient design that meets our goals.

A major problem that opposed the project progress is the delay of the financial support, which in return retards the working on the project because of lack of the tools and parts required,

6.3 Recommendations

For better future efforts in the filed of solar energy, the following recommendations and tips are made as we passed this experience.

- Renewable energy researches must be supported and financed for its importance next years. Palestine has very promising future in the area of solar energy systems and it does have a huge amount of unused source of power.

- Solar energy suppliers and companies have to take place in the economical field of Palestine, they will gain benefits by time, and by time installing solar systems would be cheaper, faster, easier and more popular.

- More researches must be applied in the economical feasibility of using solar energy and building solar stations in Palestine.

- Supporting the concept of solar trackers in a larger scales and studied plans, the system we built is able to move two more panels with the same power consume and approximately the same cost and design dimensions, if it can increase the output power of each by 20% to 30%, then those three panels can cover the price of a fourth one, the larger the scale of the solar tracker the more benefit you got while the same tracking concept is applied and small modifications in your design limitations will take place.

- Some courses that deal with energy types and its calculations must be taught at the university to help students in their energy related researches, especially in the filed of the renewable energy studies as it gains a larger global attention by time.

- Also courses that are related to microcontroller specially the PIC microcontroller should be worked with and taught, they are very important for embedded systems and industrial applications.

- The most important recommendation is that the university must prepare a large lab for graduation projects to help students to work in, since the graduation lab that is running now is not sufficient to all students, and other labs are not always opened to students to work in, as a result you might lose your day if the lab teacher is out of his work or in vacation.

• More financial support and administration's attention and care must be paid for the graduation projects; they are the completions of its student and the apparent part of its academic skills and efforts.

• Renewable energy and scientific research department in the university must increase its support for the graduation project in this field; it must embrace such concepts and turn them into beneficial and economical plans in future.

• The university must Strengthen it's relation with scientific institutions and colleges outside Hebron, it should market the students' graduation projects, be proud of them and let others know about, an annual journal includes such thoughts and information would be great idea that could help improve the university picture and reputation and might give it's student more opportunities to compete with other universities and improve their experience.

• The University must work up on turning the concepts of the graduation project into commercial applicable plans and projects.

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Appendices

Appendix (A) : Solar Panel KC40T

Appendix (B) : Solsum 6.6c Charging controller

Appendix (C) : Power Kingdom battery 40Ah

Appendix (D) : Installation manual KC40T

Appendix (E) : PIC 18f4550 features, Timer2, PWM & ADC

Appendix (F) : L298N H-bridge

Appendix (G) : Programming code of PIC

Appendix (A)

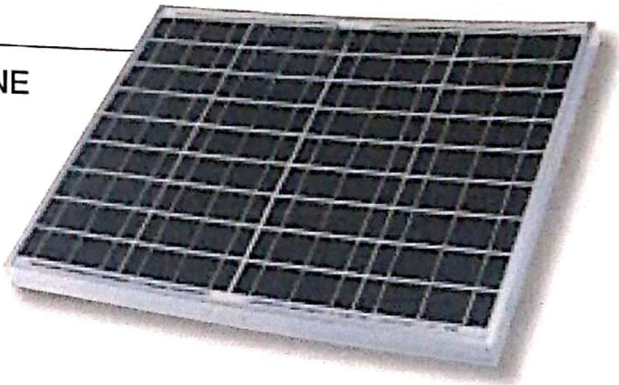
Solar Panel KC40T

THE NEW VALUE FRONTIER

KYOCERA

KC40T-1

HIGH EFFICIENCY POLYCRYSTALLINE PHOTOVOLTAIC MODULE



TÜV IEC 61215

Kyocera is "**ISO9001**" certified and registered.
TUVdotCOM Internet platform for tested quality and service ID 0000007146.

MODEL KC40T-1

HIGHLIGHTS OF KYOCERA PHOTOVOLTAIC MODULES

Kyocera's advanced cell processing technology and automated production facilities produce a highly efficient polycrystalline photovoltaic module.
The conversion efficiency of the Kyocera solar cell is 16%.
These cells are encapsulated between a tempered glass cover and a pottant with back sheet to provide efficient protection from the severest environmental conditions.
The entire laminate is installed in an anodized aluminum frame to provide structural strength and ease of installation.

APPLICATIONS

Grid-Connected Systems

- Residential Solar Power Systems
- Public and Industrial Solar Power Systems

Stand-Alone Solar Power Systems for

- Villages in remote areas
- Homes and summer cottages
- Microwave / Radio repeater stations
- Medical facilities in rural areas
- Emergency communication
- Water quality and environmental data monitoring
- Drinking water and livestock water pumping
- Small-scale irrigation pumping
- Cathodic protection
- Aviation obstruction lights
- Environmental data monitoring
- Railway signals
- Street lighting
- Small-scale desalination

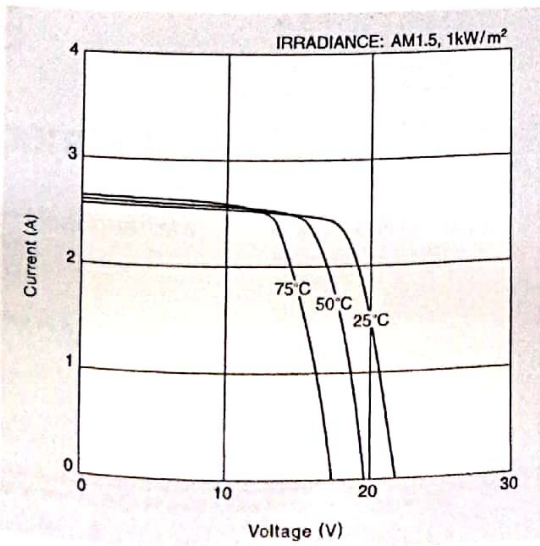
LIMITED PERFORMANCE WARRANTY

※2 years limited warranty on material and workmanship
※25 years limited warranty on power output.

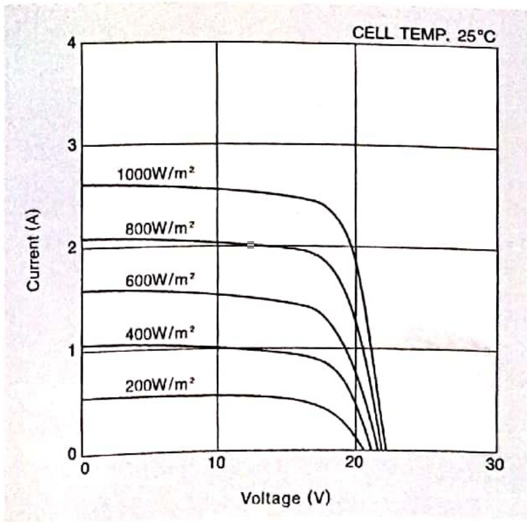
(Long term output warranty shall guarantee that loss of output is not more than 10% of the minimum warranty value of the product specifications within 12 years and is not more than 20% within 25 years after the purchase of the product by customer. The output values shall be those measured under Kyocera standard measurement conditions. Regarding the warranty conditions in detail, please refer to Warranty issued by Kyocera.)

ELECTRICAL CHARACTERISTICS

Current-Voltage characteristics of Photovoltaic Module KC40T-1 at various cell temperatures

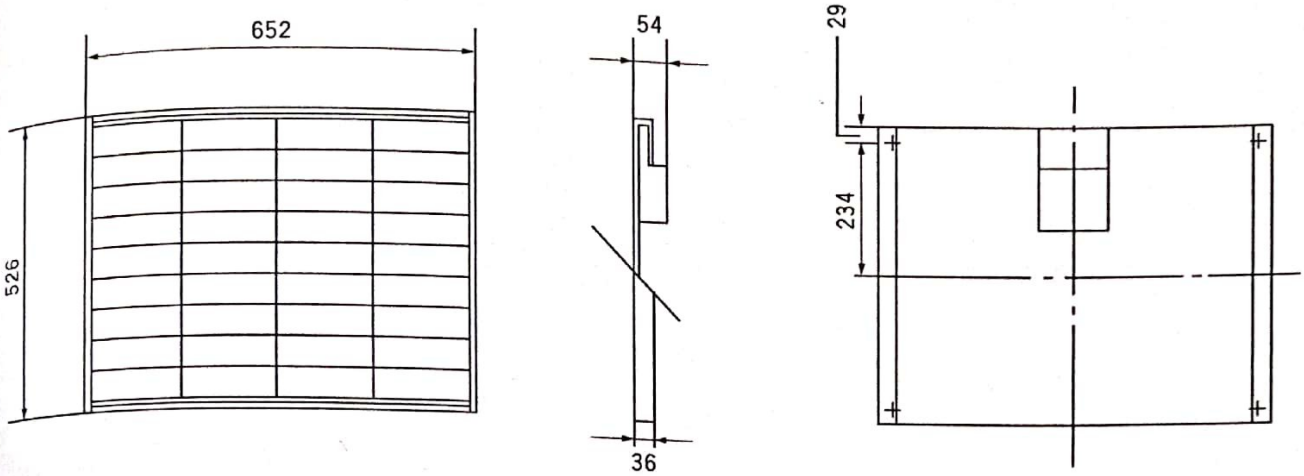


Current-Voltage characteristics of Photovoltaic Module KC40T-1 at various irradiance levels



Physical Specifications

(Unit : mm)



Specifications

Electrical Data		
aximum Power(Pmax)	[W]	43
olerance	[%]	+15/−5
aximum Power Voltage	[V]	17.4
aximum Power Current	[A]	2.48
pen Circuit Voltage (Voc)	[V]	21.7
hort Circuit Current (Isc)	[A]	2.65
emp. coefficient of Voc	[V/℃]	-8.21×10^{-2}
emp. coefficient of Isc	[A/℃]	1.06×10^{-3}
OCT	[℃]	47
ax System Voltage	[V]	750

Dimension		
Length	[mm]	526
Width	[mm]	652
Depth without box	[mm]	36
Weight	[kg]	4.5

Cells	
Number per module	36
Cell Technology	Polycrystalline
Cell Shape	Rectangular

Note : The electrical specifications are under test conditions of Irradiance of 1kw/m², Spectrum of 1.5 air mass and cell temperature of 25°C.
Kyocera reserves the right to modify these specifications without notice.

ase contact our office to obtain details without hesitation.

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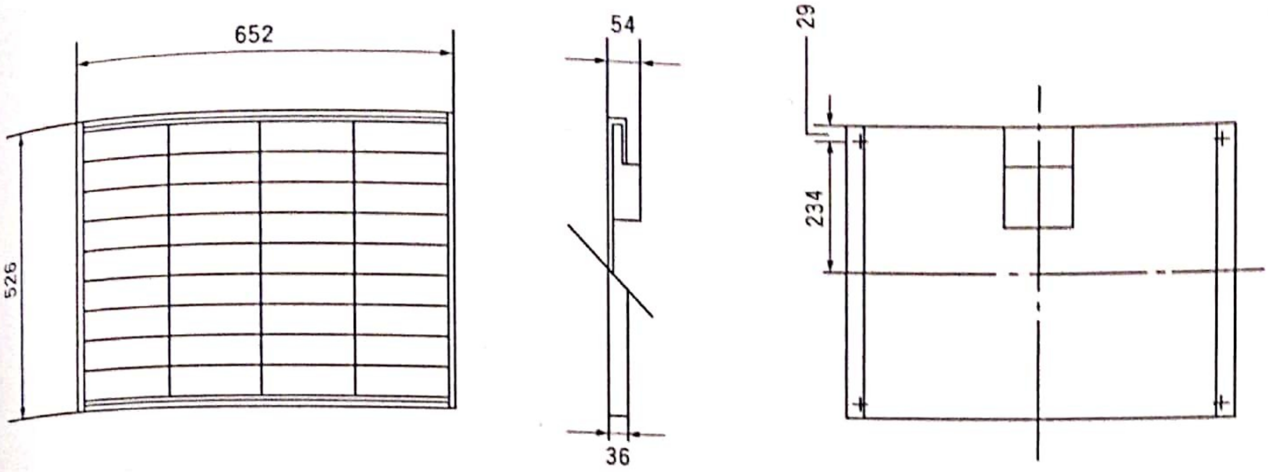
Tel:(22)2331-8590 Fax:(22)2330-6276

hysical Specifications

(Unit : mm)



Specifications

Electrical Data		
aximum Power(Pmax)	[W]	43
lerance	[%]	+15/−5
aximum Power Voltage	[V]	17.4
aximum Power Current	[A]	2.48
pen Circuit Voltage (Voc)	[V]	21.7
ort Circuit Current (Isc)	[A]	2.65
mp. coefficient of Voc	[V/℃]	-8.21×10^{-2}
mp. coefficient of Isc	[A/℃]	1.06×10^{-3}
CT	[℃]	47
x System Voltage	[V]	750

Dimension		
Length	[mm]	526
Width	[mm]	652
Depth without box	[mm]	36
Weight	[kg]	4.5

Cells	
Number per module	36
Cell Technology	Polycrystalline
Cell Shape	Rectangular

Note : The electrical specifications are under test conditions of Irradiance of 1kw/m², Spectrum of 1.5 air mass and cell temperature of 25℃.
Kyocera reserves the right to modify these specifications without notice.

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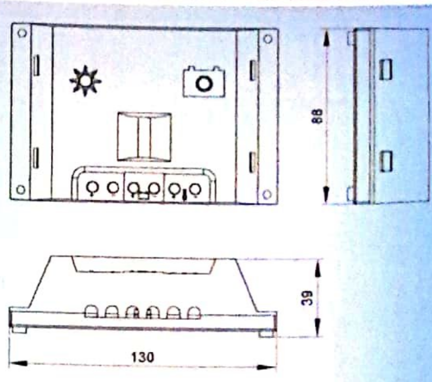
Appendix (B)

Solsum 6.6c Charging controller

Solar Charge Controller



Power class **5 A - 10 A**

0 A 50 A 100 A 150 A

Steca Solsum

5.0c, 6.6c, 8.0c, 8.8c, 10.10c

One of Steca's bestsellers are the photovoltaic controllers of the Solsum C series which are used in small solar home systems with a 5 to 10 Amp solar charging and load current capacity (up to 240 Wp). The Solsum C series was launched in 2004 as a redesign of the Solsum X series. The C series advantages are large connection terminals, fully covered PCB and a easy to understand display. The electronic board uses automized through hole technology for easy local maintenance.

Certificates

- approved for Worldbank funded projects in Indonesia by TÜV
- listed for Worldbank funded projects in Bangladesh, China, Laos, Nepal, Sri Lanka, Uganda
- compliant to the use in tropical areas (DIN IEC 68 part 2-30)
- conform to European Standards (CE)
- manufactured in an ISO 9001 facility

...ar Charge Controller	Solsum 5.0c	Solsum 8.0c	Solsum 6.6c	Solsum 8.8c	Solsum 10.10c
...em voltage	12 V / (24 V)				
...module input short circuit current	5 A	8 A	6 A	8 A	10 A
...load output current	5 A	8 A	6 A	8 A	10 A
	-	-	✓	✓	✓
...self consumption	4 mA				
...of charge voltage (float)	13.7 V / (27.4 V)				
...charge voltage	14.4 V / (28.8 V)				
...lization charge	-				
...nection setpoint (LVR)	without LVR		12.6 V / (25.2 V)		
...discharge protection (LVD)	without LVD		11,1 V / (22,2 V)		
...ent temperature allowed	-25 °C...+50 °C				
...al size (fine / single wire)	2.5 mm² / 4 mm²				
...ure protection class	IP 22				
...t	165 g				
...ions l x w x h	130 x 88 x 39 mm				

...data at 25 °C / 77 °F

Features

- voltage regulation
- PWM shunt battery charging
- boost charging
- float charging
- automatic load reconnection
- automatic selection of voltage (12 V / 24 V)
- temperature compensation
- positive grounding
- (or) negative grounding on one terminal

Electronic Protections

- high voltage disconnect (HVD)
- low voltage disconnect (LVD), not 5.0c & 8.0c
- reverse polarity of solar modules
- reverse polarity of load & battery
- short circuit of solar modules
- short circuit of load
- over temperature
- over voltage
- lightning protection by varistor
- low electronic interference (EMC)
- open circuit battery
- reverse current at night

Displays

two LEDs

(1) battery charging LED
- by solar module = green LED in "sun" symbol

(2) battery voltage LED
- end of charge voltage = green LED
- battery voltage level = red & yellow & green LED
- load disconnect prewarning = fast flashing red LED
- deep discharge protection = slowly flashing red LED

Solar Charge Controllers
5.6 / 6.6 / 5.0
8.8 / 8.0

Discharge Protection
Overcharge Protection
Temperature Compensation
System Voltage 12/24 V
Gassing Regulation

CE

Please read these instructions completely before installation!

Instructions and description of controllers with overcharge and overdischarge protection, gasing regulation and temperature compensation.
In photovoltaic solar systems lead batteries are often used for storing solar current. These batteries have to be protected against overcharging and overdischarging. The Solsum controllers Solsum 5.0 / 5.6 / 6.6 / 8.0 / 8.8 fulfill both tasks in one device. They can be used for 12 and 24 V systems.

Overcharge Protection
When the battery exceeds the final charge voltage, it starts to gas. As this process is temperature dependent, the final charge voltage is adapted automatically to the ambient temperature by a built-in sensor. Strong gasing leads to an electrolyte loss and finally to the destruction of the battery. The battery is however not charged completely when the final charge voltage is reached, so that the current flow should not be interrupted. The charge controller therefore reduces the current flow into the battery just as much as that the final charge voltage is not exceeded. This procedure is called "IU-charging" which is considered to be especially fast and gentle. The reduction of the current flow is effected by very quick, temporary short-circuiting (pulse width modulation) of the solar generator.

Gasing Regulation
The final charge voltage is changed in dependence with the discharge level. When a lead battery is operated without gas development for a longer time, there is the danger of a harmful acid layering. This acid layering can be avoided by limited, controlled gasing. This function is fulfilled by the gasing regulation. The gasing regulation switches off the overcharge protection until the so-called final gasing voltage is reached. Furthermore the gasing regulation increases the final charge voltage during high cyclisation. By this temperature dependent function, the battery capacity is better used.

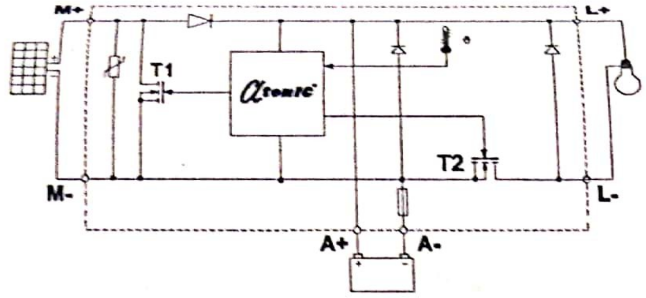


Fig. 1: Circuit Diagram

Overdischarge protection
The batteries have to be protected from overdischarge, as it would be destroyed otherwise. Therefore the charge controller protectes the battery from overdischarge by disconnecting the loads when the voltage falls below the final charge voltage. After the battery has been recharged by the solar generator and the reconnection voltage is reached, the useres are again reconnected.

Displays:
The controller contains a green and a LED which can change its colour from red via yellow to green in ten different colour . The green LED is on as soon as there is energy from the module. When the controller starts to limit the charge current, this LED is flashing. The LED which can change its colour shows the voltage by its colour. Before the load is switched off, this LED starts to flash fast. When the load is switched off, this LED flashes slowly.

Do not forget that the connected users do not use more current than admissable for your regulator.

Advice for Installation:
The controller has to be installed possibly near the battery and must not be exposed to direct weather conditions. The controller is to be operated in well-ventilated rooms. The connection terminals have to point downwards when it is installed. In order to activate the protective functions the controller has to be connected with solar generator, battery and users.
All system components i.e. solar generator, battery users and controller have to be coordinated concerning voltage. This is to be checked before intallation! Pay attention to the correct nominal voltage! Ask your dealer when you are in doubt!

Following order has to be obeyed when installing your controller:

1. Connect the battery with the controller at the screw terminal. The biggest possible cable diameter is recommended in order to keep a voltage drop and a connection terminal heating as low as possible (see technical data). Only when the controller is installed with short circuit proof cables, an isolation of the battery cable can be omitted. Otherwise a fuse has to be inserted directly at the plus pole of the battery in order to avoid a short circuit. Both components have to be installed in the same room in near distance, as the sensor for temperature determination is integrated into the controller.
2. Connect the modules with the controller and note the correct polarity.
3. At last connect users

For installation see figure 2.

Pay attention to the correct polarity!

Sources of errors:
Inversion of battery polarity. The fuse blows, it has to be replaced by the same type.

Inversion of module polarity: This is to be avoided.

Inversion of the polarity of the load: The users (lights, radio etc.) can be damaged before the fuse blows. A huge energy quantity is stored in the battery. In the case of a short circuit, this energy can be set free within a short time and a fire at the place of the short circuit can be caused because of heat.

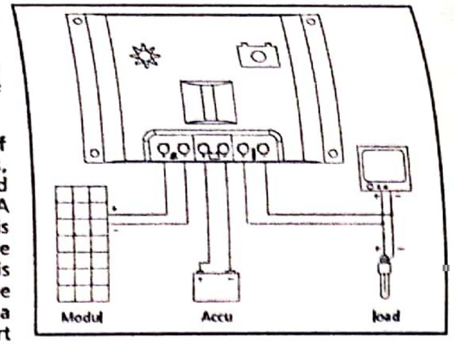


Fig. 2: Connection

Attention:
1 Avoid short circuits: danger of fire!
2. Users which may not switched off must be installed near the battery and protected by a fuse (e. g. position lights)
3. Sparkings can develop especially in direct current systems during installation and operation. Do not install PV-components in rooms where easy flammable gases mixtures can develop (e. g. by gas bottles, laquers, solvents). Consult your dealer when in doubt.

Adjustment of nominal voltage
Automatic adjustment to the system voltage when the regulator is installed.

When you pay attention to this instrucions your solar system will give you many years of pleasure. The battery reaches a life of ten years or longer. As the solar module and the charge controller have a considerably higher life age, only the battery has to be exchanged. A defect battery can be recognised that although the above-mentioned charging takes place, the overdischarge protection switches off the users already after a short time.

Technical Data at 25°C:

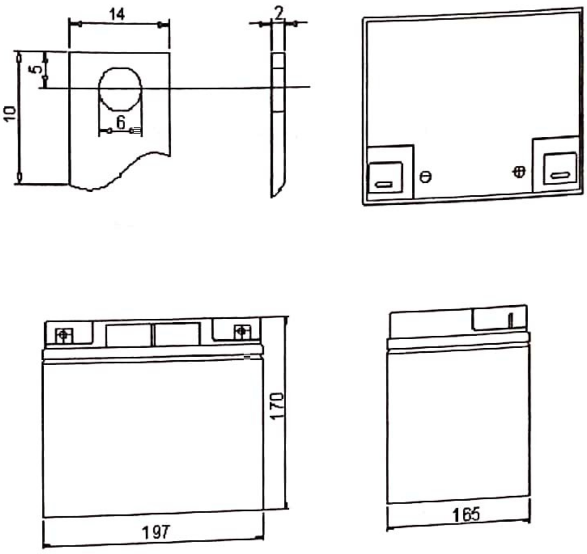
Controller Type	5.6/6.6	8.8	5.0	8.0
Nominal Voltage	12 V			
Max. module current	6 A	8 A	5 A	8 A
Max. load current	6 A	8 A	-*	-*
Max. own consumption	4 mA			
Final charge voltage				
Normale	13,7 V			
Temperature compensation	4 mV / K / cell			
Overdischarge disconnection				
Constant	11,1 V	11,1 V	-*	-*
Reconnection	12,6 V	12,6 V	-*	-*
Gasing regulation				
"Gasing active" voltage	12,4 V			
Final gassing voltage	14,4 V			
Temperature Compensation	- 3 mV / K / cell			
Fuse	7,5A	10 A	7,5 A	10 A
Admissable ambient temperature	-25 °C ... + 50 °C			
Dimensions	130 x 88 x 39 mm			
Connection terminal	2,5 mm² / 4mm²			
Weight	165 g			

(For 24V systems voltages are to be doubled!)
* No load disconnect. Only fused with 7,5 and 10A.

Appendix (C)

Power King Battery 40Ah

POWER KINGDOM **Sealed Lead-Acid Batteries** **PK40-12• 12V40Ah• •**



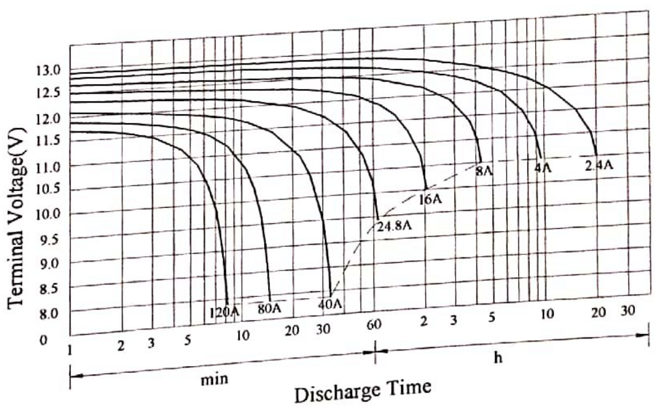
● **Specifications**

Nominal Voltage		12V
Rated Capacity		40Ah
Dimensions	Total Height	6.69 inches (170mm)
	Height	6.69 inches (170mm)
	Length	7.76 inches (197mm)
	Width	6.50 inches (165mm)
Approximate Weight		27.5lbs. (12.5kg)

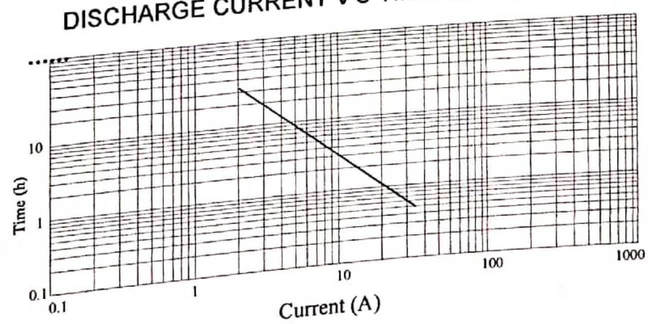
● **Characteristic**

Capacity 77°F(25°C)	20h rate (2.0A)		40Ah
	10h rate (37.2A)		37.2Ah
	5h rate (6.40A)		32Ah
	1h rate (24.8A)		24.8Ah
	15 min rate (70.4A)		17.6Ah
Internal Resistance	Full Charged Battery 77°F(25°C)		8.5m• •
Capacity Affected by Temperature (20h rate)	104°F(40°C)		102%
	77°F(25°C)		100%
	32°F(0°C)		85%
	5°F(-15°C)		65%
Self-Discharge 68°F(20°C) (Capacity after)	3 month storage		90%
	6 month storage		80%
	12 month storage		60%
Max. Discharge Current 77°F(25°C)	400A(5s)		
Terminal	T4 /T12		
Charge (Constant Voltage,25°C)	Cycle	14.4~14.7V(-24mV/°C) max. current:12A	
	Float	13.6~13.8V(-18mV/°C)	

DISCHARGE CHARACTERISTICS AT 25° C(77° F)*

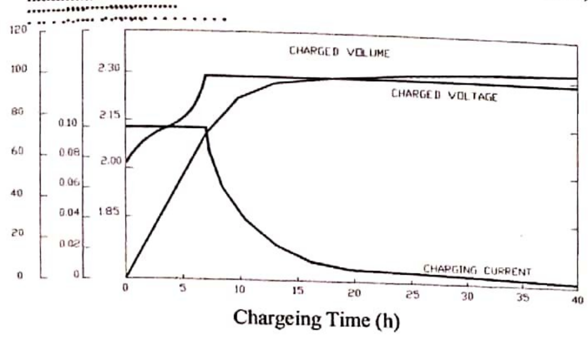


DISCHARGE CURRENT V'S TIME 25° C(77° F)

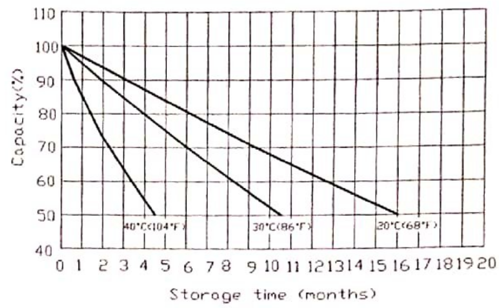


***The above data are of average values, and can be obtained within 3 charge/discharge cycles. These are not minimum values.**

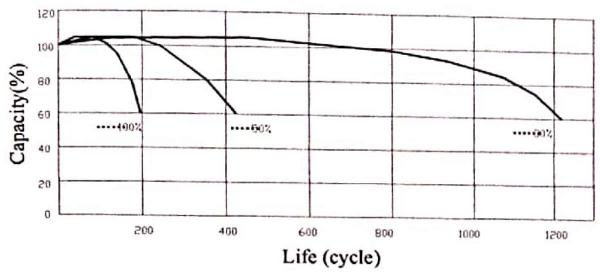
Constant-Voltage Characteristic (100% Discharged)



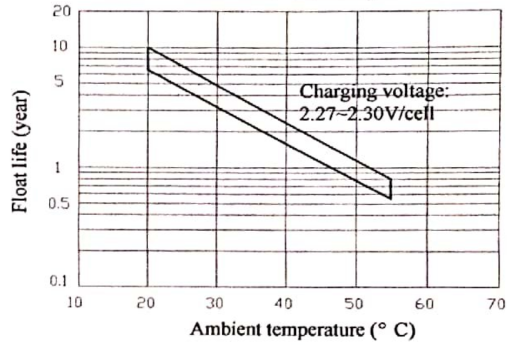
Self Discharge Characteristic



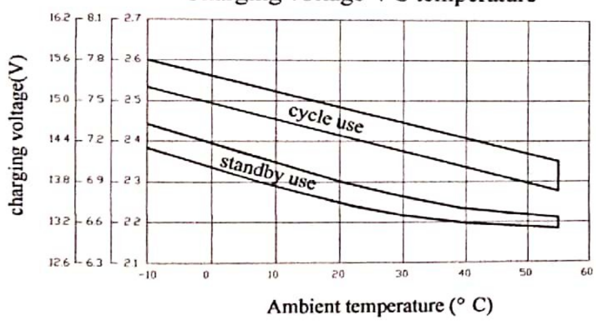
Cycle service life



Float service life V'S temperature

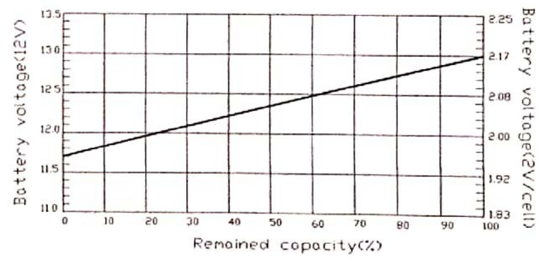


Charging voltage V'S temperature



Open circuit voltage and remaining capacity

(At 20° C)



- **Constant wattage discharge at stipulated cut-off voltages: Watt/Ah/Cell at 25°C**

Final voltage (V/cell)	5m	10m	15m	30m	45m	1h	2h	5h	10h	20h
1.60V	214	154	122	75.6	56.8	47.9	26.7	12.4	7.00	3.10
1.65V	204	150	119	75.2	56.2	46.6	26.5	12.4	7.00	3.10
1.70V	199	146	115	72.8	54.3	45.0	26.5	12.4	7.00	3.10
1.75V	182	136	109	71.7	53.5	44.3	25.9	12.2	6.90	3.10
1.80V	163	127	102	69.0	51.5	44.0	25.4	12.1	6.80	3.00

Appendix (D)

Installation Manual KC40T

KYOCERA

INSTALLATION MANUAL

FOR THE

KC-SERIES

OF

SOLAR PHOTOVOLTAIC POWER MODULES

Please read this manual carefully before installing the modules.

KYOCERA 6C-203828-1

1. INTRODUCTION

As the world leader in development and application of high technology ceramic/silica materials, Kyocera offers a wide range of highly efficient and reliable crystalline silicon solar photovoltaic (PV) power modules. Kyocera began to extensively research PV technology in 1975 and commenced manufacturing operations in 1978. Since then, Kyocera has supplied millions of cells and modules throughout the world. With years of experience and state-of-the-art technology, Kyocera provides the highest quality PV power modules in a range of sizes designed to meet the requirements of the most demanding energy and power users worldwide.

2. POWER MODULES

Kyocera power modules consist of a series of electrically interconnected crystalline silicon solar cells. Which are permanently laminated within a pottant and encapsulated between a tempered glass cover plate and a back sheet. The entire laminate is secured within an anodized aluminum frame for structural strength, ease of installation, and to protect the cells from the most severe environmental conditions.

3. APPLICATIONS

Kyocera modules are a reliable, virtually maintenance-free direct current (DC) power source, designed to operate most efficiently in sunlight. Kyocera modules are ideal to power remote homes, recreational vehicles, water pumps, telecommunication systems and many other applications either with or without the use of storage batteries.

4. WARNINGS

Solar modules generate electricity when exposed to light. Arrays of many modules can cause lethal shock and burn hazards. Only authorized and trained personnel should have access to these modules. To reduce the risk of electrical shock or burns, modules may be covered with an opaque material during installation to avoid shocks or burns. Do not touch live terminals with bare hands. Use insulated tools for electrical connections.

PERMIT

- Before installing your solar system, contact local authorities to determine the necessary permit, installation and inspection requirements.

INSTALLATION AND OPERATION

- Systems should be installed by qualified personnel only. The system involves electricity, and can be dangerous if the personnel are not familiar with the appropriate safety procedures.
- Do not step on the module.
- Although KYOCERA modules are quite rugged, the glass can be broken (and the module will no longer work properly) if it is dropped or hit by tools or other objects.
- Sunlight shall not be concentrated on the module.
- The module frame is made of anodized aluminum, and therefore corrosion can occur if the module is subject to a salt water environment with contact to a rack of another type of metal.(Electrolysis Corrosion) If required, PVC or stainless steel washers can be placed between the solar module frame and support structure to prevent this type of corrosion.
- The solar module frame must be attached to a support structure using ¼" or M6 stainless steel hardware in a minimum of four (4) places symmetrical on the solar module. The stainless steel hardware used for securing the module frame should secured with an applied torque of 6 foot-pounds (8 Newton-meters).
- Module support structures that are to be used to support Kyocera Solar modules should be wind rated and approved for use by the appropriate local and civil codes prior to installation.

GROUNDING

- All module frames and mounting racks must be properly grounded in accordance with local and national electrical codes.

INSPECTION

- Follow the requirements of applicable local and national electrical codes.

BATTERY

- When solar modules are used to charge batteries, the battery must be installed in a manner which will protect the performance of the system and the safety of its users. **Follow the battery manufacturer's guidelines concerning installation, operation and maintenance recommendations.** In general, the battery (or battery bank) should be away from the main flow of people and animal traffic. Select a battery site that is protected from sunlight, rain, snow, debris, and is well ventilated. Most batteries generate hydrogen gas when charging, which can be explosive. Do not light matches or create sparks near the battery bank. When a battery is installed outdoors, it should be placed in an insulated and ventilated battery case specifically designed for the purpose.

5. SITE SELECTION

In most applications, KC modules should be installed in a location where they will receive maximum sunlight throughout the year. In the Northern Hemisphere, the modules should typically face south, and in the Southern Hemisphere, the modules should typically face north. Modules facing 30 degrees away from true South (or North) will lose approximately 10 to 15 per cent of their power output. If the module faces 60 degrees away from true South (or North), the power loss will be 20 to 30 per cent. When choosing a site, avoid trees, buildings or obstructions which could cast shadows on the solar modules especially during the winter months when the arc of the sun is lowest over the horizon.

6. MODULE TILT ANGLE

Kyocera solar modules produce the most power when they are pointed directly at the sun. For installations where the solar modules are attached to a permanent structure, the solar modules should be tilted for optimum winter performance. As a rule, if the system power production is adequate in the winter, it will be satisfactory during the rest of the year. The module tilt angle is measured between the solar modules and the ground (Figure 1). Refer to Table 1 for the recommended module tilt angle at your site.

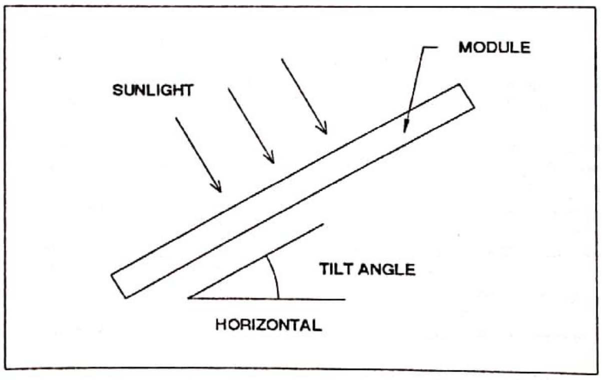


Figure 1. Module Tilt Angle

Table 1. **Recommended Tilt Angles for Fixed Systems—Based on Winter Performance**

SITE LATITUDE IN DEGREES	FIXED TILT ANGLE
0° TO 15	15°
15° TO 25°	SAME AS LATITUDE
25° TO 30°	LATITUDE + 5°
30° TO 35°	LATITUDE + 10°
35° TO 40°	LATITUDE + 15°
40° +	LATITUDE + 20°

7. INSTALLING KC MODULES

The frame of each module has 0.28" ϕ diameter (7 mm) mounting holes (Refer to Module Mounting Specifications). These are used to secure the modules to the supporting structure. An example of a ground mounted structure is shown in Figure 2. The four holes close to the corners of the module are most often used for attachment. Refer to the Mounting Specification Specifications for the position of these holes. Clearance between the module frame and the mounting surface may be required to prevent the junction box from touching the surface, and to circulate cooling air around the back of the module. If the modules are to be installed on the roof or wall of a building, the standoff method or the rack method is recommended.

STAND-OFF METHOD: The modules are supported parallel to the surface of the building wall or roof. Clearance between the module frames and surface of the wall or roof is required to prevent wiring damage and to allow air to circulate behind the module.
The recommended stand-off height is 4.5 in. (about 115 mm) If other mounting means are employed, this may affect the Listing For Fire Class Ratings.

RACK: The supporting frame is used to mount modules at correct tilt angles. The modules are not designed for integral mounting as part of a roof or wall. The mounting design may have an impact on the fire resistance.

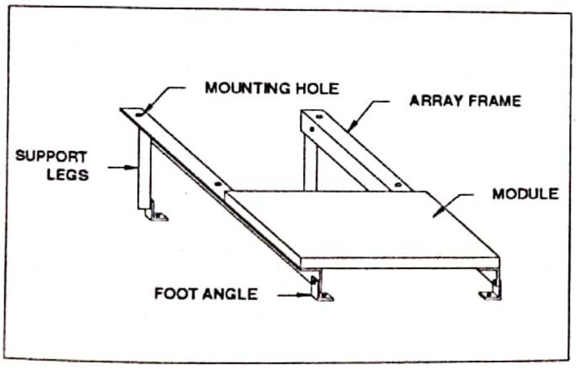


Figure 2. Basic Rack or Standoff Mounting Structure

8. MODULE WIRING

As shown in Module Mounting Specifications, all of the KC modules utilize the Type G junction box except the KC85T, KC85TS, KC125TM, KC130TM modules which utilize the Type M junction box (see J-box details). This junction box, located on the back side of the module, is weatherproof and is designed to be used with standard wiring or conduit connections. Kyocera recommends that all wiring and electrical connections comply with the 2002 National Electrical Code (NEC). A cable clamp with a minimum rating of IP65 must be used to maintain the weatherproof integrity of the junction box.Bypass diodes are preinstalled at factory

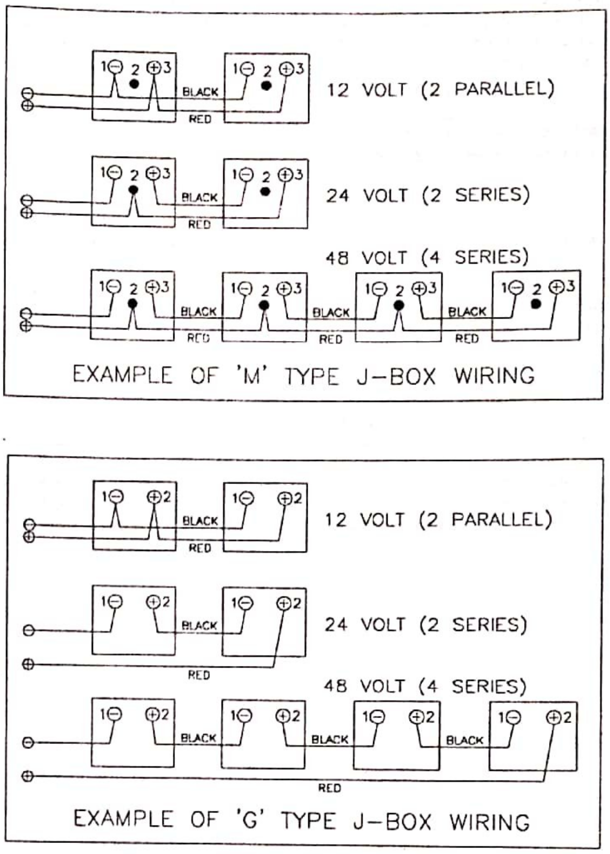


Figure 3. Standard Wiring Examples

To wire Kyocera modules:

A Determine the nominal system array voltage of your system. Each panel is equivalent to a 12 VDC nominal block. Standard array voltages 12, 24 and 48 volt are shown as examples in Figure 3.

B. Open the "G" or "M" box cover by loosening the screws in the cover.

C. The wire used to interconnect the solar modules may be single or two conductors, from 14 AWG (2.08 mm^2) up to 10 AWG (5.26 mm^2) gauge stranded copper wire, in a "SUNLIGHT RESISTANT" jacket UF cable. This cable is suitable for applications where wiring is exposed to the direct rays of the sun. The maximum and minimum outer diameters of the cable that may be used with the cable connector are 8 mm and 6 mm respectively (Figure 4).

D. Using a flat blade screwdriver, remove only the appropriate "KNOCK-OUTS" from the sides of the "G" or "M" box.

E. Route wires through the knock-outs and clamps refer to installation example (see Figure 5).

F. Gently hand tighten the terminal screws with cross tip (Phillips head) screwdriver. Do not over tighten, as the terminal can be damaged.

G. The output wiring from the final module is generally run to a separate array junction box. In commercial system, this wiring from the array box to the next component (i.e. fuse box. or charge regulator, etc.) is generally run in conduit. The maximum electrical rating of an acceptable series fuse is 6~12 amperes.

H. After checking that module wiring is correct, close and secure all the junction boxes. Use a Phillips head screw driver to secure all screws on the junction box cover to ensure a waterproof seal.

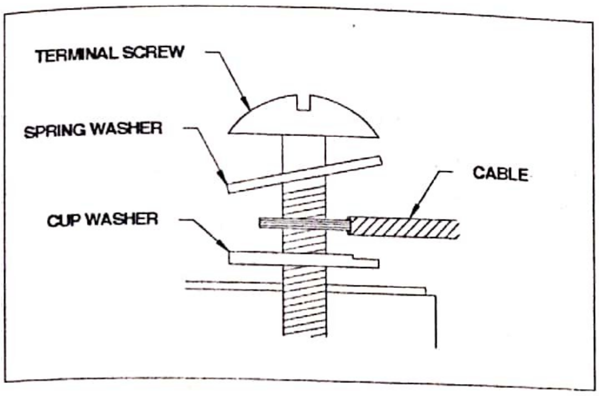


Figure 4. Ring or Spade Terminal Connectors

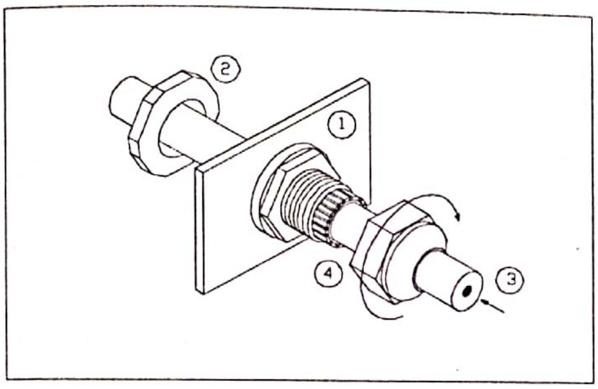


Figure 5. Installation Example of Cable Clamp

9. GROUNDING

We recommend you attach all module frames to an earth ground. Attach a separate ground wire to one of the holes marked 'ground' on the module frame with a screw and bonding or external tooth washer. This is to ensure positive electrical contact with the frame. The racks must also be grounded unless they are mechanically connected by nuts and bolts to the grounded modules. The array frame shall be grounded in accordance with NEC Art 250.

10. BLOCKING DIODES

Blocking diodes are typically placed between the battery and the PV module output to prevent battery discharge at night. Kyocera modules are made of polycrystalline cells with high electrical "back flow" resistance to nighttime battery discharging. As a result, KYOCERA modules do not contain a blocking diode when shipped from the factory. Most PV charge regulators do have nighttime disconnect feature, however.

11. BYPASS DIODES

Partial shading of an individual module in a 12 volt or higher source circuit string (i.e. two or more modules connected in series) can cause a reverse voltage across the shaded module. Current is then forced through the shaded area by the other modules.

When a bypass diode is wired in parallel with the series string, the forced current will flow through the diode and bypass the shaded module, thereby minimizing module heating and array current losses.

For 12-volt systems and higher: Each module junction box has a diagram illustrating the proper orientation of the bypass diode installed between two of the terminal screws. When individual series strings of solar modules are connected together in parallel, bypass diodes should be used in each modules junction box.

Diodes that are used as bypass diodes must:

- Have a Rated Average Forward Current [$I_{F(AV)}$] Above maximum system current at highest module operating temperature.
- Have a Rated Repetitive Peak Reverse Voltage [V_{RRM}] Above maximum system voltage at lowest module operating temperature.

12. MAINTENANCE

Kyocera modules are designed for long life and require very little maintenance. Under most weather conditions, normal rainfall is sufficient to keep the module glass surface clean. If dirt build-up becomes excessive, clean the glass surface only with a soft cloth using mild detergent and water. USE CAUTION WHEN CLEANING THE BACK SURFACE OF THE MODULE TO AVOID PENETRATING THE PVF SHEET. Modules that are mounted flat (0° tilt angle) should be cleaned more often, as they will not "self clean" as effectively as modules mounted at a 15° tilt or greater. Once a year, check the tightness of terminal screws and the general condition of the wiring. Also, check to be sure that mounting hardware is tight. Loose connections will result in a damaged module or array.

13. SPECIFICATIONS

The electrical and physical specifications can be found at the end of this document (Table2) .

NOTES

- The electrical characteristics are indicated values of Pmax under standard test conditions (irradiance of 1KW/m^2, AM 1.5 spectrum, and cell temperature of 25℃).
- Under certain conditions, a photovoltaic module is likely to produce more current and / or voltage than reported at standard test conditions. Accordingly, the values of Isc and Voc marked on this module should be multiplied by a factor of 1.25 when determining component voltage ratings, conductor ampacities, fuse sizes, and sizes of regulators which are connected to the PV output. Refer to Section 690-8 of the National Electrical Code for an additional multiplying factor of 1.25 which may also be applicable.

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Table 2. **Kyocera KC Series Module Specification**

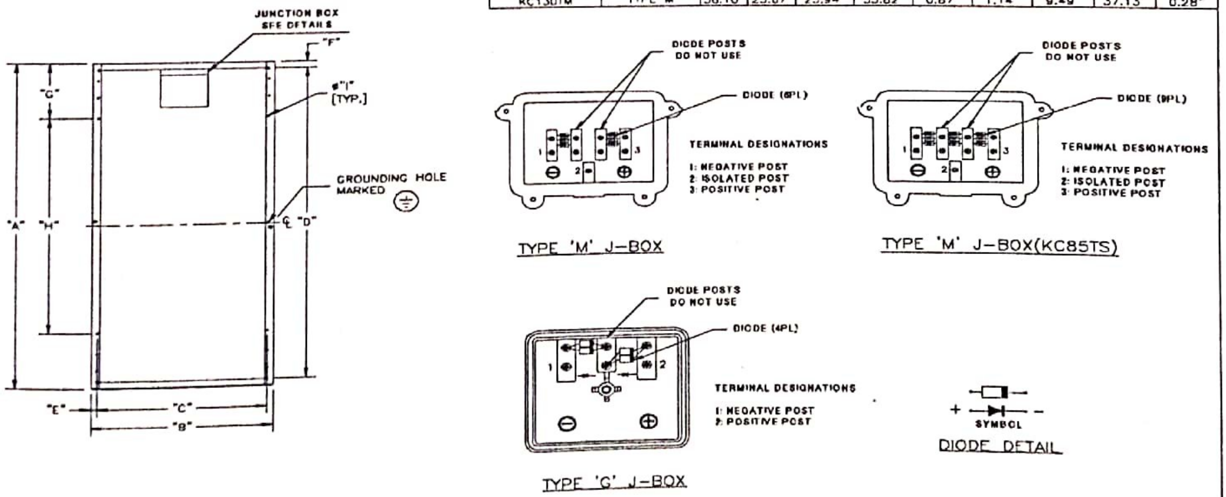
Electrical Characteristics:@ STC							
Model Number	KC40T	KC50T	KC65T	KC85T	KC85TS	KC125TM	KC130TM
Rated Power, Watts (Pmax)	43 + 15% − 5%	54 + 15% − 5%	65 + 10% − 5%	87 + 10% − 5%	87 + 10% − 5%	125 + 10% − 5%	130 + 10% − 5%
Open Circuit Voltage (Voc)	21.7	21.7	21.7	21.7	21.7	21.7	21.9
Short Circuit Current (Isc)	2.65	3.31	3.99	5.34	5.34	8.00	8.02
Voltage at Load (Vpm)	17.4	17.4	17.4	17.4	17.4	17.4	17.6
Current at Load (Ipm)	2.48	3.11	3.75	5.02	5.02	7.20	7.39
Maximum System Voc	600	600	600	600	600	600	600
Factory Installed Bypass Diode (Qty)	Yes (2)	Yes (2)	Yes (2)	Yes (2)	Yes (3)	Yes (2)	Yes (2)
Series Fuse Rating (Amps)	6	6	6	7	7	12	12
Thermal Characteristics:							
Temp. coefficient of Voc (V/℃)	-8.21×10^{-2}	-8.21×10^{-2}	-8.21×10^{-2}	-8.21×10^{-2}	-8.21×10^{-2}	-8.21×10^{-2}	-8.21×10^{-2}
Temp. coefficient of Isc (A/℃)	1.06×10^{-3}	1.33×10^{-3}	1.59×10^{-3}	2.12×10^{-3}	2.12×10^{-3}	3.18×10^{-3}	3.18×10^{-3}
Temp. coefficient of Vpm (V/℃)	-9.31×10^{-2}	-9.32×10^{-2}	-9.32×10^{-2}	-9.32×10^{-2}	-9.32×10^{-2}	-9.31×10^{-2}	-9.31×10^{-2}
Physical Characteristics:							
Model Number	KC40T	KC50T	KC65T	KC85T	KC85TS	KC125TM	KC130TM
Length, Inches (mm)	20.7(526)	25.2 (639)	29.6 (751)	39.6(1007)	39.6(1007)	56.1(1425)	56.1(1425)
Width, Inches (mm)	25.7(652)	25.7 (652)	25.7 (652)	25.7 (652)	25.7 (652)	25.7 (652)	25.7 (652)
Depth (frame), Inches (mm)	1.42(36)	1.42 (36)	1.42 (36)	1.42 (36)	1.42 (36)	1.42 (36)	1.42 (36)
Depth (including j-box), inches (mm)	2.1(54)	2.1(54)	2.1(54)	2.3(58)	2.3(58)	2.3(58)	2.3(58)
Weight, Pounds (kg)	9.9(4.5)	11.0 (5.0)	13.2 (6.0)	18.3 (8.3)	18.3 (8.3)	26.9 (12.2)	26.9 (12.2)
Mounting Hole Diameter inches (mm)	0.28" (7) Qty – 4	0.28" (7) Qty – 4	0.28" (7) Qty – 8	0.28" (7) Qty – 8	0.28" (7) Qty – 8	0.28" (7) Qty – 8	0.28" (7) Qty – 8
Grounding Hole Diameter inches (mm)	0.28" (7) Qty – 2	0.28" (7) Qty – 2	0.28" (7) Qty – 2	0.28" (7) Qty – 2	0.28" (7) Qty – 2	0.28" (7) Qty – 2	0.28" (7) Qty – 2

NOTES

(1) Standard Test Conditions of irradiance of 1000 W/m^2, spectrum of 1.5 air mass, and cell temperature of 25 deg C.
(2) Normal Operational Cell Temperature (NOCT) of 800 W/m^2, spectrum of 1.5 air mass, and cell temperature of 25 deg C.
(3) See module drawing for mounting and grounding hole locations.

MODULE DIMENSIONS

MODULE	J-BOX	DIM. A	DIM. B	DIM. C	DIM. D	DIM. E	DIM. F	DIM. G	DIM. H	DIM. I
KC40T	TYPE G	20.71"	25.67"	24.13"	18.43"	0.77"	1.14"	–	18.42"	0.28"
KC50T	TYPE C	25.18"	25.67"	24.13"	22.87"	0.77"	1.14"	–	22.87"	0.28"
KC65T	TYPE G	29.57"	25.67"	24.13"	27.28"	0.77"	1.14"	9.49"	10.59"	0.28"
KC85T	TYPE M	39.65"	25.67"	24.13"	37.30"	0.77"	1.14"	9.49"	20.67"	0.28"
KC85TS	TYPE M	39.65"	25.67"	24.13"	37.36"	0.77"	1.14"	9.49"	20.67"	0.28"
KC125TM	TYPE M	56.10"	25.67"	23.94"	53.82"	0.87"	1.14"	9.49"	37.13"	0.28"
KC130TM	TYPE M	56.10"	25.67"	23.94"	53.82"	0.87"	1.14"	9.49"	37.13"	0.28"



Appendix (E)

PIC 18f4550 features, Timer2, PWM & ADC

MICROCHIP

PIC18F2455/2550/4455/4550

28/40/44-Pin, High-Performance, Enhanced Flash, USB Microcontrollers with nanoWatt Technology

Universal Serial Bus Features:

- USB V2.0 Compliant
- Low Speed (1.5 Mb/s) and Full Speed (12 Mb/s)
- Supports Control, Interrupt, Isochronous and Bulk Transfers
- Supports up to 32 Endpoints (16 bidirectional)
- 1-Kbyte Dual Access RAM for USB
- On-Chip USB Transceiver with On-Chip Voltage Regulator
- Interface for Off-Chip USB Transceiver
- Streaming Parallel Port (SPP) for USB streaming transfers (40/44-pin devices only)

Power-Managed Modes:

- Run: CPU on, peripherals on
- Idle: CPU off, peripherals on
- Sleep: CPU off, peripherals off
- Idle mode currents down to 5.8 μA typical
- Sleep mode currents down to 0.1 μA typical
- Timer1 Oscillator: 1.1 μA typical, 32 kHz, 2V
- Watchdog Timer: 2.1 μA typical
- Two-Speed Oscillator Start-up

Flexible Oscillator Structure:

- Four Crystal modes, including High Precision PLL for USB
- Two External Clock modes, up to 48 MHz
- Internal Oscillator Block:
  - 8 user-selectable frequencies, from 31 kHz to 8 MHz
  - User-tunable to compensate for frequency drift
- Secondary Oscillator using Timer1 @ 32 kHz
- Dual Oscillator options allow microcontroller and USB module to run at different clock speeds
- Fail-Safe Clock Monitor:
  - Allows for safe shutdown if any clock stops

Peripheral Highlights:

- High-Current Sink/Source: 25 mA/25 mA
- Three External Interrupts
- Four Timer modules (Timer0 to Timer3)
- Up to 2 Capture/Compare/PWM (CCP) modules:
  - Capture is 16-bit, max. resolution 5.2 ns ($T_{CY}/16$)
  - Compare is 16-bit, max. resolution 83.3 ns (T_{CY})
  - PWM output: PWM resolution is 1 to 10-bit
- Enhanced Capture/Compare/PWM (ECCP) module:
  - Multiple output modes
  - Selectable polarity
  - Programmable dead time
  - Auto-shutdown and auto-restart
- Enhanced USART module:
  - LIN bus support
- Master Synchronous Serial Port (MSSP) module supporting 3-wire SPI (all 4 modes) and I²C™ Master and Slave modes
- 10-bit, up to 13-channel Analog-to-Digital Converter module (A/D) with Programmable Acquisition Time
- Dual Analog Comparators with Input Multiplexing

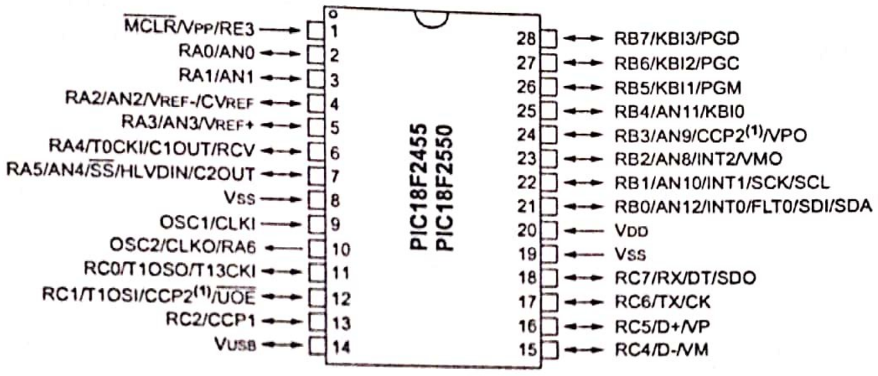
Special Microcontroller Features:

- C Compiler Optimized Architecture with optional Extended Instruction Set
- 100,000 Erase/Write Cycle Enhanced Flash Program Memory typical
- 1,000,000 Erase/Write Cycle Data EEPROM Memory typical
- Flash/Data EEPROM Retention: > 40 years
- Self-Programmable under Software Control
- Priority Levels for Interrupts
- 8 x 8 Single-Cycle Hardware Multiplier
- Extended Watchdog Timer (WDT):
  - Programmable period from 41 ms to 131s
- Programmable Code Protection
- Single-Supply 5V In-Circuit Serial Programming™ (ICSP™) via two pins
- In-Circuit Debug (ICD) via two pins
- Optional dedicated ICD/ICSP port (44-pin devices only)
- Wide Operating Voltage Range (2.0V to 5.5V)

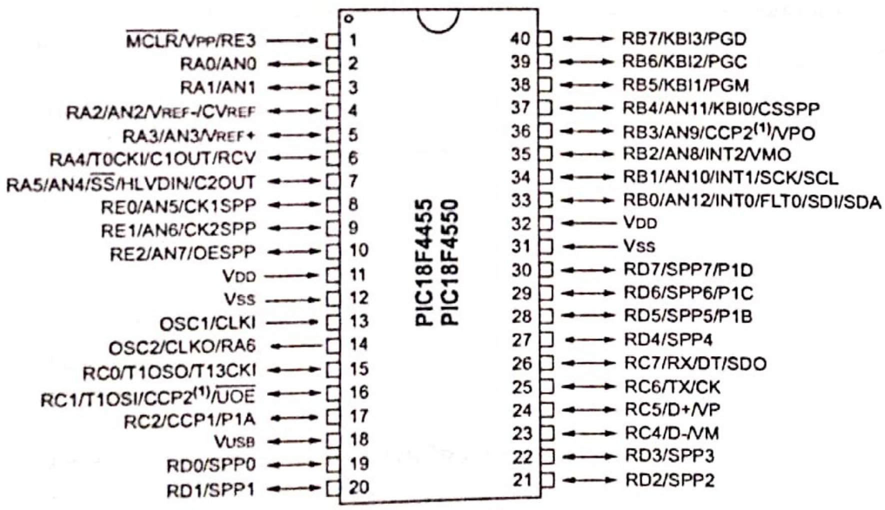
Device	Program Memory		Data Memory		I/O	10-Bit A/D (ch)	CCP/ECCP (PWM)	SPP	MSSP		EAUSART	Comparators	Timers 8/16-Bit
	Flash (bytes)	# Single-Word Instructions	SRAM (bytes)	EEPROM (bytes)					SPI	Master I²C™			
PIC18F2455	24K	12288	2048	256	24	10	2/0	No	Y	Y	1	2	1/3
PIC18F2550	32K	16384	2048	256	24	10	2/0	No	Y	Y	1	2	1/3
PIC18F4455	24K	12288	2048	256	35	13	1/1	Yes	Y	Y	1	2	1/3
PIC18F4550	32K	16384	2048	256	35	13	1/1	Yes	Y	Y	1	2	1/3

Pin Diagrams

28-Pin PDIP, SOIC



40-Pin PDIP



Note 1: RB3 is the alternate pin for CCP2 multiplexing.

13.0 TIMER2 MODULE

The Timer2 module timer incorporates the following features:

- 8-bit timer and period registers (TMR2 and PR2, respectively)
- Readable and writable (both registers)
- Software programmable prescaler (1:1, 1:4 and 1:16)
- Software programmable postscaler (1:1 through 1:16)
- Interrupt on TMR2 to PR2 match
- Optional use as the shift clock for the MSSP module

The module is controlled through the T2CON register (Register 13-1) which enables or disables the timer and configures the prescaler and postscaler. Timer2 can be shut off by clearing control bit, TMR2ON (T2CON<2>), to minimize power consumption.

A simplified block diagram of the module is shown in Figure 13-1.

13.1 Timer2 Operation

In normal operation, TMR2 is incremented from 00h on each clock (FOSC/4). A 2-bit counter/prescaler on the clock input gives direct input, divide-by-4 and divide-by-16 prescale options. These are selected by the prescaler control bits, T2CKPS1:T2CKPS0 (T2CON<1:0>). The value of TMR2 is compared to that of the period register, PR2, on each clock cycle. When the two values match, the comparator generates a match signal as the timer output. This signal also resets the value of TMR2 to 00h on the next cycle and drives the output counter/postscaler (see **Section 13.2 "Timer2 Interrupt"**).

The TMR2 and PR2 registers are both directly readable and writable. The TMR2 register is cleared on any device Reset, while the PR2 register initializes at FFh. Both the prescaler and postscaler counters are cleared on the following events:

- a write to the TMR2 register
- a write to the T2CON register
- any device Reset (Power-on Reset, $\overline{\text{MCLR}}$ Reset, Watchdog Timer Reset or Brown-out Reset)

TMR2 is not cleared when T2CON is written.

REGISTER 13-1: T2CON: TIMER2 CONTROL REGISTER

U-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
—	T2OUTPS3	T2OUTPS2	T2OUTPS1	T2OUTPS0	TMR2ON	T2CKPS1	T2CKPS0
bit 7							bit 0

Legend:			
R = Readable bit	W = Writable bit	U = Unimplemented bit, read as '0'	
-n = Value at POR	'1' = Bit is set	'0' = Bit is cleared	x = Bit is unknown

bit 7 **Unimplemented:** Read as '0'

bit 6-3 **T2OUTPS3:T2OUTPS0**: Timer2 Output Postscale Select bits
0000 = 1:1 Postscale
0001 = 1:2 Postscale
•
•
•
1111 = 1:16 Postscale

bit 2 **TMR2ON**: Timer2 On bit
1 = Timer2 is on
0 = Timer2 is off

bit 1-0 **T2CKPS1:T2CKPS0**: Timer2 Clock Prescale Select bits
00 = Prescaler is 1
01 = Prescaler is 4
1x = Prescaler is 16

13.2 Timer2 Interrupt

Timer2 also can generate an optional device interrupt. The Timer2 output signal (TMR2 to PR2 match) provides the input for the 4-bit output counter/postscaler. This counter generates the TMR2 match interrupt flag which is latched in TMR2IF (PIR1<1>). The interrupt is enabled by setting the TMR2 Match Interrupt Enable bit, TMR2IE (PIE1<1>).

A range of 16 postscale options (from 1:1 through 1:16 inclusive) can be selected with the postscaler control bits, T2OUTPS3:T2OUTPS0 (T2CON<6:3>).

13.3 TMR2 Output

The unscaled output of TMR2 is available primarily to the CCP modules, where it is used as a time base for operations in PWM mode.

Timer2 can be optionally used as the shift clock source for the MSSP module operating in SPI mode. Additional information is provided in **Section 19.0 "Master Synchronous Serial Port (MSSP) Module"**.

FIGURE 13-1: TIMER2 BLOCK DIAGRAM

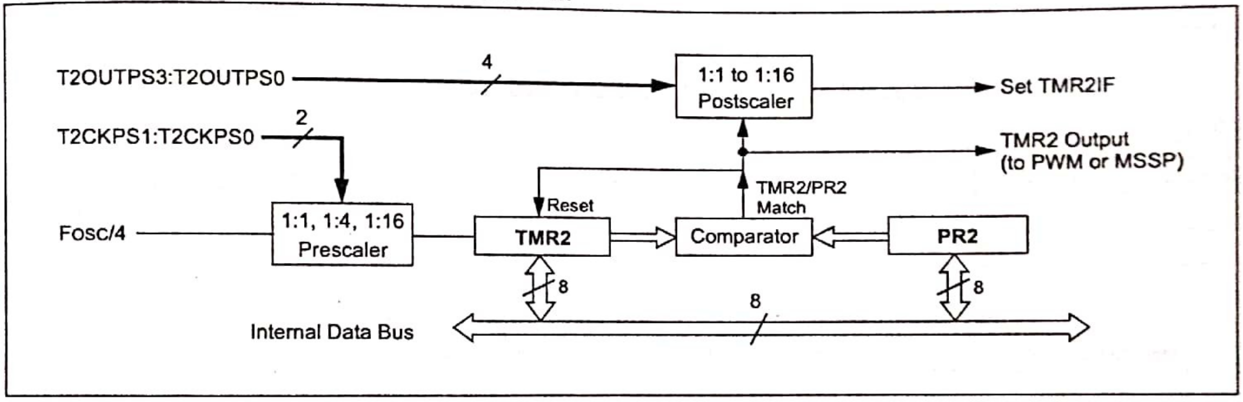


TABLE 13-1: REGISTERS ASSOCIATED WITH TIMER2 AS A TIMER/COUNTER

Name	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0	Reset Values on page
INTCON	GIE/GIEH	PEIE/GIEL	TMR0IE	INT0IE	RBIE	TMR0IF	INT0IF	RBIF	51
PIR1	SPPIF[(1)]	ADIF	RCIF	TXIF	SSPIF	CCP1IF	TMR2IF	TMR1IF	54
PIE1	SPPIE[(1)]	ADIE	RCIE	TXIE	SSPIE	CCP1IE	TMR2IE	TMR1IE	54
IPR1	SPPIP[(1)]	ADIP	RCIP	TXIP	SSPIP	CCP1IP	TMR2IP	TMR1IP	54
TMR2	Timer2 Register								52
T2CON	—	T2OUTPS3	T2OUTPS2	T2OUTPS1	T2OUTPS0	TMR2ON	T2CKPS1	T2CKPS0	52
PR2	Timer2 Period Register								52

Legend: — = unimplemented, read as '0'. Shaded cells are not used by the Timer2 module.

Note 1: These bits are unimplemented on 28-pin devices; always maintain these bits clear.

15.0 CAPTURE/COMPARE/PWM (CCP) MODULES

PIC18F2455/2550/4455/4550 devices all have two CCP (Capture/Compare/PWM) modules. Each module contains a 16-bit register, which can operate as a 16-bit Capture register, a 16-bit Compare register or a PWM Master/Slave Duty Cycle register.

In 28-pin devices, the two standard CCP modules (CCP1 and CCP2) operate as described in this chapter. In 40/44-pin devices, CCP1 is implemented as an Enhanced CCP module, with standard Capture and Compare modes and Enhanced PWM modes. The ECCP implementation is discussed in **Section 16.0 "Enhanced Capture/Compare/PWM (ECCP) Module"**.

The Capture and Compare operations described in this chapter apply to all standard and Enhanced CCP modules.

Note:	Throughout this section and **Section 16.0 "Enhanced Capture/Compare/PWM (ECCP) Module"**, references to the register and bit names for CCP modules are referred to generically by the use of 'x' or 'y' in place of the specific module number. Thus, "CCPxCON" might refer to the control register for CCP1, CCP2 or ECCP1. "CCPxCON" is used throughout these sections to refer to the module control register regardless of whether the CCP module is a standard or Enhanced implementation.

REGISTER 15-1: CCPxCON: STANDARD CCPx CONTROL REGISTER

U-0	U-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
—[(1)]	—[(1)]	DCxB1	DCxB0	CCPxM3	CCPxM2	CCPxM1	CCPxM0
bit 7							bit 0

Legend:			
R = Readable bit	W = Writable bit	U = Unimplemented bit, read as '0'	
-n = Value at POR	'1' = Bit is set	'0' = Bit is cleared	x = Bit is unknown

bit 7-6 **Unimplemented:** Read as '0'[(1)]

bit 5-4 **DCxB1:DCxB0**: PWM Duty Cycle Bit 1 and Bit 0 for CCPx Module

Capture mode:
Unused.

Compare mode:
Unused.

PWM mode:
These bits are the two LSbs (bit 1 and bit 0) of the 10-bit PWM duty cycle. The eight MSbs of the duty cycle are found in CCPR1L.

bit 3-0 **CCPxM3:CCPxM0**: CCPx Module Mode Select bits

- `0000` = Capture/Compare/PWM disabled (resets CCPx module)
- `0001` = Reserved
- `0010` = Compare mode: toggle output on match (CCPxIF bit is set)
- `0011` = Reserved
- `0100` = Capture mode: every falling edge
- `0101` = Capture mode: every rising edge
- `0110` = Capture mode: every 4th rising edge
- `0111` = Capture mode: every 16th rising edge
- `1000` = Compare mode: initialize CCPx pin low; on compare match, force CCPx pin high (CCPxIF bit is set)
- `1001` = Compare mode: initialize CCPx pin high; on compare match, force CCPx pin low (CCPxIF bit is set)
- `1010` = Compare mode: generate software interrupt on compare match (CCPxIF bit is set, CCPx pin reflects I/O state)
- `1011` = Compare mode: trigger special event, reset timer, start A/D conversion on CCP2 match (CCPxIF bit is set)
- `11xx` = PWM mode

Note 1: These bits are not implemented on 28-pin devices and are read as '0'.

15.1 CCP Module Configuration

Each Capture/Compare/PWM module is associated with a control register (generically, CCPxCON) and a data register (CCPRx). The data register, in turn, is comprised of two 8-bit registers: CCPRxL (low byte) and CCPRxH (high byte). All registers are both readable and writable.

15.1.1 CCP MODULES AND TIMER RESOURCES

The CCP modules utilize Timers 1, 2 or 3, depending on the mode selected. Timer1 and Timer3 are available to modules in Capture or Compare modes, while Timer2 is available for modules in PWM mode.

TABLE 15-1: CCP MODE – TIMER RESOURCE

CCP/ECCP Mode	Timer Resource
Capture	Timer1 or Timer3
Compare	Timer1 or Timer3
PWM	Timer2

The assignment of a particular timer to a module is determined by the Timer to CCP enable bits in the T3CON register (Register 14-1). Both modules may be active at any given time and may share the same timer resource if they are configured to operate in the same mode (Capture/Compare or PWM) at the same time. The interactions between the two modules are summarized in Figure 15-2. In Timer1 in Asynchronous Counter mode, the capture operation will not work.

15.1.2 CCP2 PIN ASSIGNMENT

The pin assignment for CCP2 (Capture input, Compare and PWM output) can change, based on device configuration. The CCP2MX Configuration bit determines which pin CCP2 is multiplexed to. By default, it is assigned to RC1 (CCP2MX = 1). If the Configuration bit is cleared, CCP2 is multiplexed with RB3.

Changing the pin assignment of CCP2 does not automatically change any requirements for configuring the port pin. Users must always verify that the appropriate TRIS register is configured correctly for CCP2 operation, regardless of where it is located.

TABLE 15-2: INTERACTIONS BETWEEN CCP1 AND CCP2 FOR TIMER RESOURCES

CCP1 Mode	CCP2 Mode	Interaction
Capture	Capture	Each module can use TMR1 or TMR3 as the time base. The time base can be different for each CCP.
Capture	Compare	CCP2 can be configured for the Special Event Trigger to reset TMR1 or TMR3 (depending upon which time base is used). Automatic A/D conversions on trigger event can also be done. Operation of CCP1 could be affected if it is using the same timer as a time base.
Compare	Capture	CCP1 be configured for the Special Event Trigger to reset TMR1 or TMR3 (depending upon which time base is used). Operation of CCP2 could be affected if it is using the same timer as a time base.
Compare	Compare	Either module can be configured for the Special Event Trigger to reset the time base. Automatic A/D conversions on CCP2 trigger event can be done. Conflicts may occur if both modules are using the same time base.
Capture	PWM(1)	None
Compare	PWM(1)	None
PWM(1)	Capture	None
PWM(1)	Compare	None
PWM(1)	PWM	Both PWMs will have the same frequency and update rate (TMR2 interrupt).

Note 1: Includes standard and Enhanced PWM operation.

15.2 Capture Mode

In Capture mode, the CCPRxH:CCPRxL register pair captures the 16-bit value of the TMR1 or TMR3 registers when an event occurs on the corresponding CCPx pin. An event is defined as one of the following:

- every falling edge
- every rising edge
- every 4th rising edge
- every 16th rising edge

The event is selected by the mode select bits, CCPxM3:CCPxM0 (CCPxCON<3:0>). When a capture is made, the interrupt request flag bit, CCPxIF, is set; it must be cleared in software. If another capture occurs before the value in register CCPRx is read, the old captured value is overwritten by the new captured value.

15.2.1 CCP PIN CONFIGURATION

In Capture mode, the appropriate CCPx pin should be configured as an input by setting the corresponding TRIS direction bit.

Note:	If RB3/CCP2 or RC1/CCP2 is configured as an output, a write to the port can cause a capture condition.

15.2.2 TIMER1/TIMER3 MODE SELECTION

The timers that are to be used with the capture feature (Timer1 and/or Timer3) must be running in Timer mode or Synchronized Counter mode. In Asynchronous Counter mode, the capture operation will not work. The timer to be used with each CCP module is selected in the T3CON register (see **Section 15.1.1 "CCP Modules and Timer Resources"**).

15.2.3 SOFTWARE INTERRUPT

When the Capture mode is changed, a false capture interrupt may be generated. The user should keep the CCPxIE interrupt enable bit clear to avoid false interrupts. The interrupt flag bit, CCPxIF, should also be cleared following any such change in operating mode.

15.2.4 CCP PRESCALER

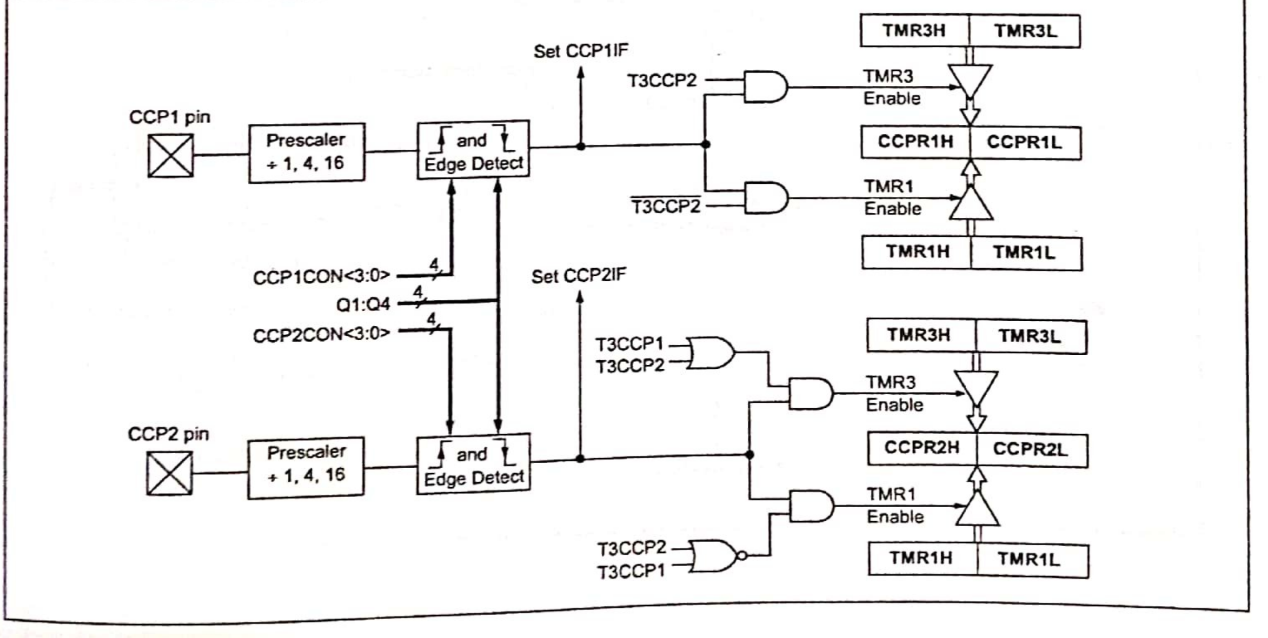
There are four prescaler settings in Capture mode. They are specified as part of the operating mode selected by the mode select bits (CCPxM3:CCPxM0). Whenever the CCP module is turned off or Capture mode is disabled, the prescaler counter is cleared. This means that any Reset will clear the prescaler counter.

Switching from one capture prescaler to another may generate an interrupt. Also, the prescaler counter will not be cleared, therefore, the first capture may be from a non-zero prescaler. Example 15-1 shows the recommended method for switching between capture prescalers. This example also clears the prescaler counter and will not generate the "false" interrupt.

EXAMPLE 15-1: CHANGING BETWEEN CAPTURE PRESCALERS (CCP2 SHOWN)

```
CLRF   CCP2CON      ; Turn CCP module off
MOVLW  NEW_CAPT_PS  ; Load WREG with the
                    ; new prescaler mode
                    ; value and CCP ON
MOVWF  CCP2CON      ; Load CCP2CON with
                    ; this value
```

FIGURE 15-1: CAPTURE MODE OPERATION BLOCK DIAGRAM



 Preliminary

15.3 Compare Mode

In Compare mode, the 16-bit CCPRx register value is constantly compared against either the TMR1 or TMR3 register pair value. When a match occurs, the CCPx pin can be:

- driven high
- driven low
- toggled (high-to-low or low-to-high)
- remain unchanged (that is, reflects the state of the I/O latch)

The action on the pin is based on the value of the mode select bits (CCPxM3:CCPxM0). At the same time, the interrupt flag bit, CCPxIF, is set.

15.3.1 CCP PIN CONFIGURATION

The user must configure the CCPx pin as an output by clearing the appropriate TRIS bit.

Note:	Clearing the CCP2CON register will force the RB3 or RC1 compare output latch (depending on device configuration) to the default low level. This is not the PORTB or PORTC I/O data latch.

15.3.2 TIMER1/TIMER3 MODE SELECTION

Timer1 and/or Timer3 must be running in Timer mode, or Synchronized Counter mode, if the CCP module is using the compare feature. In Asynchronous Counter mode, the compare operation may not work.

15.3.3 SOFTWARE INTERRUPT MODE

When the Generate Software Interrupt mode is chosen (CCPxM3:CCPxM0 = `1010`), the corresponding CCPx pin is not affected. Only a CCP interrupt is generated, if enabled, and the CCPxIE bit is set.

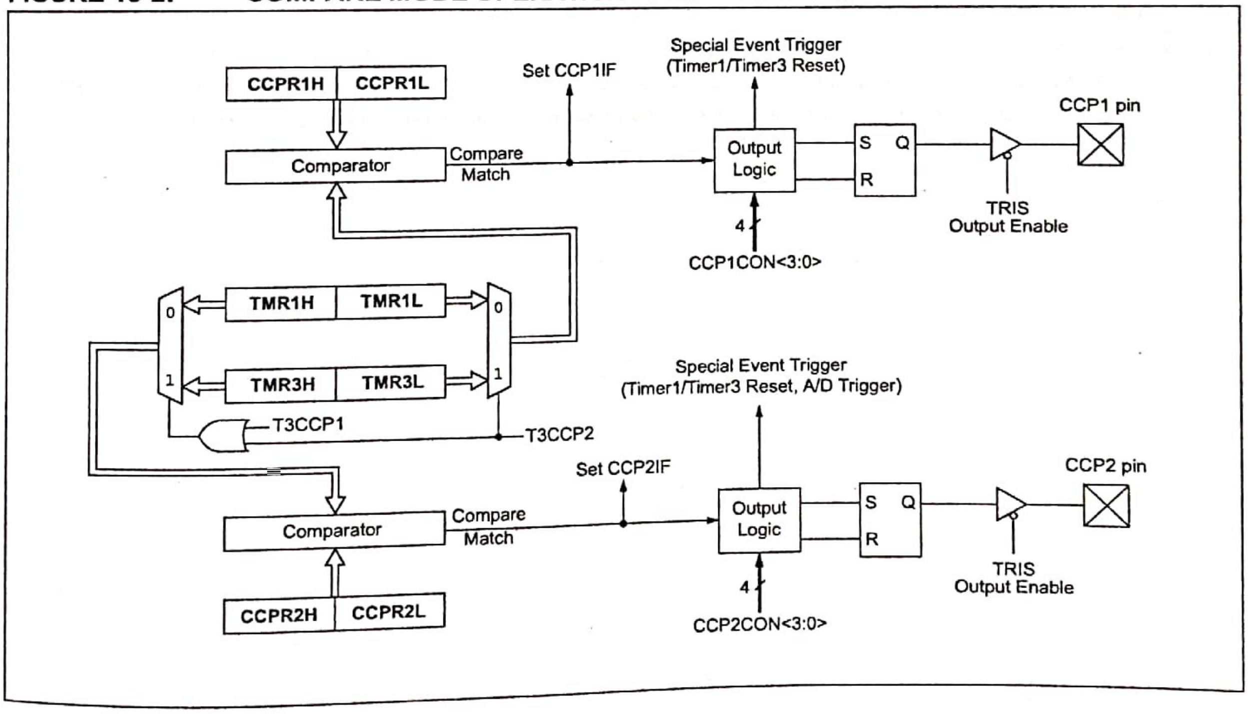
15.3.4 SPECIAL EVENT TRIGGER

Both CCP modules are equipped with a Special Event Trigger. This is an internal hardware signal generated in Compare mode to trigger actions by other modules. The Special Event Trigger is enabled by selecting the Compare Special Event Trigger mode (CCPxM3:CCPxM0 = `1011`).

For either CCP module, the Special Event Trigger resets the Timer register pair for whichever timer resource is currently assigned as the module's time base. This allows the CCPRx registers to serve as a programmable period register for either timer.

The Special Event Trigger for CCP2 can also start an A/D conversion. In order to do this, the A/D converter must already be enabled.

FIGURE 15-2: COMPARE MODE OPERATION BLOCK DIAGRAM



Preliminary

TABLE 15-3: REGISTERS ASSOCIATED WITH CAPTURE, COMPARE, TIMER1 AND TIMER3

Name	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0	Reset Values on page
INTCON	GIE/GIEH	PEIE/GIEL	TMR0IE	INT0IE	RBIE	TMR0IF	INT0IF	RBIF	51
RCON	IPEN	SBOREN(1)	—	$\overline{RI}$	$\overline{TO}$	$\overline{PD}$	$\overline{POR}$	$\overline{BOR}$	52
PIR1	SPPIF(2)	ADIF	RCIF	TXIF	SSPIF	CCP1IF	TMR2IF	TMR1IF	54
PIE1	SPPIE(2)	ADIE	RCIE	TXIE	SSPIE	CCP1IE	TMR2IE	TMR1IE	54
IPR1	SPPIP(2)	ADIP	RCIP	TXIP	SSPIP	CCP1IP	TMR2IP	TMR1IP	54
PIR2	OSCFIF	CMIF	USBIF	EEIF	BCLIF	HLVDIF	TMR3IF	CCP2IF	54
PIE2	OSCFIE	CMIE	USBIE	EEIE	BCLIE	HLVDIE	TMR3IE	CCP2IE	54
IPR2	OSCFIP	CMIP	USBIP	EEIP	BCLIP	HLVDIP	TMR3IP	CCP2IP	54
TRISB	TRISB7	TRISB6	TRISB5	TRISB4	TRISB3	TRISB2	TRISB1	TRISB0	54
TRISC	TRISC7	TRISC6	—	—	—	TRISC2	TRISC1	TRISC0	54
TMR1L	Timer1 Register Low Byte								52
TMR1H	Timer1 Register High Byte								52
T1CON	RD16	T1RUN	T1CKPS1	T1CKPS0	T1OSCEN	$\overline{T1SYNC}$	TMR1CS	TMR1ON	52
TMR3H	Timer3 Register High Byte								53
TMR3L	Timer3 Register Low Byte								53
T3CON	RD16	T3CCP2	T3CKPS1	T3CKPS0	T3CCP1	$\overline{T3SYNC}$	TMR3CS	TMR3ON	53
CCPR1L	Capture/Compare/PWM Register 1 Low Byte								53
CCPR1H	Capture/Compare/PWM Register 1 High Byte								53
CCP1CON	P1M1(2)	P1M0(2)	DC1B1	DC1B0	CCP1M3	CCP1M2	CCP1M1	CCP1M0	53
CCPR2L	Capture/Compare/PWM Register 2 Low Byte								53
CCPR2H	Capture/Compare/PWM Register 2 High Byte								53
CCP2CON	—	—	DC2B1	DC2B0	CCP2M3	CCP2M2	CCP2M1	CCP2M0	53

Legend: — = unimplemented, read as '0'. Shaded cells are not used by Capture/Compare, Timer1 or Timer3.

Note 1: The SBOREN bit is only available when BOREN<1:0> = 01; otherwise, the bit reads as '0'.

2: These bits are unimplemented on 28-pin devices; always maintain these bits clear.

15.4 PWM Mode

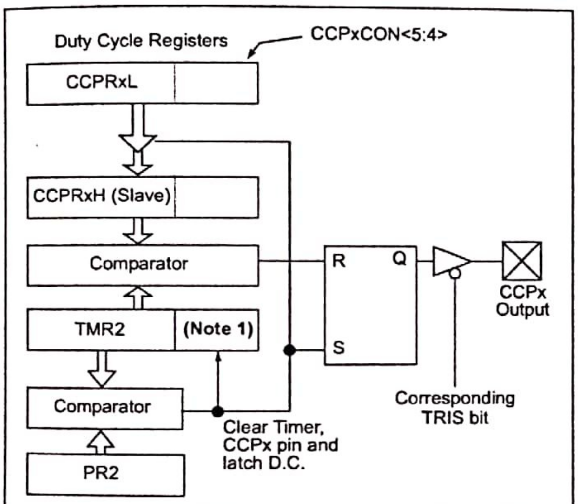
In Pulse-Width Modulation (PWM) mode, the CCPx pin produces up to a 10-bit resolution PWM output. Since the CCP2 pin is multiplexed with a PORTB or PORTC data latch, the appropriate TRIS bit must be cleared to make the CCP2 pin an output.

> **Note:** Clearing the CCP2CON register will force the RB3 or RC1 output latch (depending on device configuration) to the default low level. This is not the PORTB or PORTC I/O data latch.

Figure 15-3 shows a simplified block diagram of the CCP module in PWM mode.

For a step-by-step procedure on how to set up the CCP module for PWM operation, see **Section 15.4.4 "Setup for PWM Operation"**.

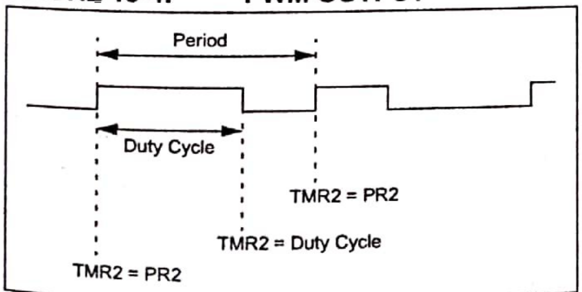
FIGURE 15-3: SIMPLIFIED PWM BLOCK DIAGRAM



Note 1: The 8-bit TMR2 value is concatenated with the 2-bit internal Q clock, or 2 bits of the prescaler, to create the 10-bit time base.

A PWM output (Figure 15-4) has a time base (period) and a time that the output stays high (duty cycle). The frequency of the PWM is the inverse of the period (1/period).

FIGURE 15-4: PWM OUTPUT



15.4.1 PWM PERIOD

The PWM period is specified by writing to the PR2 register. The PWM period can be calculated using the following formula:

EQUATION 15-1:

$$\text{PWM Period} = [(PR2) + 1] \cdot 4 \cdot T_{OSC} \cdot (\text{TMR2 Prescale Value})$$

PWM frequency is defined as 1/[PWM period].

When TMR2 is equal to PR2, the following three events occur on the next increment cycle:

- TMR2 is cleared
- The CCPx pin is set (exception: if PWM duty cycle = 0%, the CCPx pin will not be set)
- The PWM duty cycle is latched from CCPRxL into CCPRxH

> **Note:** The Timer2 postscalers (see **Section 13.0 "Timer2 Module"**) are not used in the determination of the PWM frequency. The postscaler could be used to have a servo update rate at a different frequency than the PWM output.

15.4.2 PWM DUTY CYCLE

The PWM duty cycle is specified by writing to the CCPRxL register and to the CCPxCON<5:4> bits. Up to 10-bit resolution is available. The CCPRxL contains the eight MSbs and the CCPxCON<5:4> bits contain the two LSbs. This 10-bit value is represented by CCPRxL:CCPxCON<5:4>. The following equation is used to calculate the PWM duty cycle in time:

EQUATION 15-2:

$$\text{PWM Duty Cycle} = (\text{CCPRxL:CCPxCON<5:4>}) \cdot T_{OSC} \cdot (\text{TMR2 Prescale Value})$$

CCPRxL and CCPxCON<5:4> can be written to at any time, but the duty cycle value is not latched into CCPRxH until after a match between PR2 and TMR2 occurs (i.e., the period is complete). In PWM mode, CCPRxH is a read-only register.

The CCPRxH register and a 2-bit internal latch are used to double-buffer the PWM duty cycle. This double-buffering is essential for glitchless PWM operation.

When the CCPRxH and 2-bit latch match TMR2, concatenated with an internal 2-bit Q clock or 2 bits of the TMR2 prescaler, the CCPx pin is cleared.

The maximum PWM resolution (bits) for a given PWM frequency is given by the equation:

EQUATION 15-3:

$$\text{PWM Resolution (max)} = \frac{\log\left(\frac{F_{OSC}}{F_{PWM}}\right)}{\log(2)} \text{ bits}$$

Note:	If the PWM duty cycle value is longer than the PWM period, the CCPx pin will not be cleared.

TABLE 15-4: EXAMPLE PWM FREQUENCIES AND RESOLUTIONS AT 40 MHz

PWM Frequency	2.44 kHz	9.77 kHz	39.06 kHz	156.25 kHz	312.50 kHz	416.67 kHz
Timer Prescaler (1, 4, 16)	16	4	1	1	1	1
PR2 Value	FFh	FFh	FFh	3Fh	1Fh	17h
Maximum Resolution (bits)	10	10	10	8	7	6.58

15.4.3 PWM AUTO-SHUTDOWN (CCP1 ONLY)

The PWM auto-shutdown features of the Enhanced CCP module are also available to CCP1 in 28-pin devices. The operation of this feature is discussed in detail in **Section 16.4.7 "Enhanced PWM Auto-Shutdown"**.

Auto-shutdown features are not available for CCP2.

15.4.4 SETUP FOR PWM OPERATION

The following steps should be taken when configuring the CCP module for PWM operation:

1. Set the PWM period by writing to the PR2 register.
2. Set the PWM duty cycle by writing to the CCPRxL register and CCPxCON<5:4> bits.
3. Make the CCPx pin an output by clearing the appropriate TRIS bit.
4. Set the TMR2 prescale value, then enable Timer2 by writing to T2CON.
5. Configure the CCPx module for PWM operation.

TABLE 15-5: REGISTERS ASSOCIATED WITH PWM AND TIMER2

Name	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0	Reset Values on page
INTCON	GIE/GIEH	PEIE/GIEL	TMR0IE	INT0IE	RBIE	TMR0IF	INT0IF	RBIF	51
RCON	IPEN	SBOREN(1)	—	$\overline{RI}$	$\overline{TO}$	$\overline{PD}$	$\overline{POR}$	$\overline{BOR}$	52
PIR1	SPPIF(2)	ADIF	RCIF	TXIF	SSPIF	CCP1IF	TMR2IF	TMR1IF	54
PIE1	SPPIE(2)	ADIE	RCIE	TXIE	SSPIE	CCP1IE	TMR2IE	TMR1IE	54
IPR1	SPPIP(2)	ADIP	RCIP	TXIP	SSPIP	CCP1IP	TMR2IP	TMR1IP	54
TRISB	TRISB7	TRISB6	TRISB5	TRISB4	TRISB3	TRISB2	TRISB1	TRISB0	54
TRISC	TRISC7	TRISC6	—	—	—	TRISC2	TRISC1	TRISC0	54
TMR2	Timer2 Register								52
PR2	Timer2 Period Register								52
T2CON	—	T2OUTPS3	T2OUTPS2	T2OUTPS1	T2OUTPS0	TMR2ON	T2CKPS1	T2CKPS0	52
CCPR1L	Capture/Compare/PWM Register 1 Low Byte								53
CCPR1H	Capture/Compare/PWM Register 1 High Byte								53
CCP1CON	P1M1(2)	P1M0(2)	DC1B1	DC1B0	CCP1M3	CCP1M2	CCP1M1	CCP1M0	53
CCPR2L	Capture/Compare/PWM Register 2 Low Byte								53
CCPR2H	Capture/Compare/PWM Register 2 High Byte								53
CCP2CON	—	—	DC2B1	DC2B0	CCP2M3	CCP2M2	CCP2M1	CCP2M0	53
ECCP1AS	ECCPASE	ECCPAS2	ECCPAS1	ECCPAS0	PSSAC1	PSSAC0	PSSBD1(2)	PSSBD0(2)	53
ECCP1DEL	PRSEN	PDC6(2)	PDC5(2)	PDC4(2)	PDC3(2)	PDC2(2)	PDC1(2)	PDC0(2)	53

Legend: — = unimplemented, read as '0'. Shaded cells are not used by PWM or Timer2.

Note 1: The SBOREN bit is only available when BOREN<1:0> = 01; otherwise, the bit reads as '0'.

2: These bits are unimplemented on 28-pin devices; always maintain these bits clear.

16.0 ENHANCED CAPTURE/COMPARE/PWM (ECCP) MODULE

Note:	The ECCP module is implemented only in 40/44-pin devices.

In PIC18F4455/4550 devices, CCP1 is implemented as a standard CCP module with Enhanced PWM capabilities. These include the provision for 2 or 4 output channels, user-selectable polarity, dead-band control and automatic shutdown and restart. The Enhanced features are discussed in detail in **Section 16.4 "Enhanced PWM Mode"**. Capture, Compare and single output PWM functions of the ECCP module are the same as described for the standard CCP module.

The control register for the Enhanced CCP module is shown in Register 16-1. It differs from the CCPxCON registers in PIC18F2255/2550 devices in that the two Most Significant bits are implemented to control PWM functionality.

REGISTER 16-1: CCP1CON: ECCP CONTROL REGISTER (40/44-PIN DEVICES)

R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
P1M1	P1M0	DC1B1	DC1B0	CCP1M3	CCP1M2	CCP1M1	CCP1M0
bit 7							bit 0

Legend:			
R = Readable bit	W = Writable bit	U = Unimplemented bit, read as '0'	
-n = Value at POR	'1' = Bit is set	'0' = Bit is cleared	x = Bit is unknown

bit 7-6 **P1M1:P1M0:** Enhanced PWM Output Configuration bits

If CCP1M3:CCP1M2 = 00, 01, 10:
xx = P1A assigned as Capture/Compare input/output; P1B, P1C, P1D assigned as port pins
If CCP1M3:CCP1M2 = 11:
00 = Single output: P1A modulated; P1B, P1C, P1D assigned as port pins
01 = Full-bridge output forward: P1D modulated; P1A active; P1B, P1C inactive
10 = Half-bridge output: P1A, P1B modulated with dead-band control; P1C, P1D assigned as port pins
11 = Full-bridge output reverse: P1B modulated; P1C active; P1A, P1D inactive

bit 5-4 **DC1B1:DC1B0**: PWM Duty Cycle Bit 1 and Bit 0

Capture mode:
Unused.
Compare mode:
Unused.
PWM mode:
These bits are the two LSbs of the 10-bit PWM duty cycle. The eight MSbs of the duty cycle are found in CCPR1L.

bit 3-0 **CCP1M3:CCP1M0**: Enhanced CCP Mode Select bits

0000 = Capture/Compare/PWM off (resets ECCP module)
0001 = Reserved
0010 = Compare mode, toggle output on match
0011 = Capture mode
0100 = Capture mode, every falling edge
0101 = Capture mode, every rising edge
0110 = Capture mode, every 4th rising edge
0111 = Capture mode, every 16th rising edge
1000 = Compare mode, initialize CCP1 pin low, set output on compare match (set CCP1IF)
1001 = Compare mode, initialize CCP1 pin high, clear output on compare match (set CCP1IF)
1010 = Compare mode, generate software interrupt only, CCP1 pin reverts to I/O state
1011 = Compare mode, trigger special event (CCP1 resets TMR1 or TMR3, sets CCP1IF bit)
1100 = PWM mode: P1A, P1C active-high; P1B, P1D active-high
1101 = PWM mode: P1A, P1C active-high; P1B, P1D active-low
1110 = PWM mode: P1A, P1C active-low; P1B, P1D active-high
1111 = PWM mode: P1A, P1C active-low; P1B, P1D active-low

21.0 10-BIT ANALOG-TO-DIGITAL CONVERTER (A/D) MODULE

The Analog-to-Digital (A/D) converter module has 10 inputs for the 28-pin devices and 13 for the 40/44-pin devices. This module allows conversion of an analog input signal to a corresponding 10-bit digital number.

The module has five registers:

- A/D Result High Register (ADRESH)
- A/D Result Low Register (ADRESL)
- A/D Control Register 0 (ADCON0)
- A/D Control Register 1 (ADCON1)
- A/D Control Register 2 (ADCON2)

The ADCON0 register, shown in Register 21-1, controls the operation of the A/D module. The ADCON1 register, shown in Register 21-2, configures the functions of the port pins. The ADCON2 register, shown in Register 21-3, configures the A/D clock source, programmed acquisition time and justification.

REGISTER 21-1: ADCON0: A/D CONTROL REGISTER 0

U-0	U-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
—	—	CHS3	CHS2	CHS1	CHS0	GO/$\overline{\text{DONE}}$	ADON
bit 7							bit 0

Legend:			
R = Readable bit	W = Writable bit	U = Unimplemented bit, read as '0'	
-n = Value at POR	'1' = Bit is set	'0' = Bit is cleared	x = Bit is unknown

bit 7-6 **Unimplemented:** Read as '0'

bit 5-2 **CHS3:CHS0:** Analog Channel Select bits
0000 = Channel 0 (AN0)
0001 = Channel 1 (AN1)
0010 = Channel 2 (AN2)
0011 = Channel 3 (AN3)
0100 = Channel 4 (AN4)
0101 = Channel 5 (AN5)(1,2)
0110 = Channel 6 (AN6)(1,2)
0111 = Channel 7 (AN7)(1,2)
1000 = Channel 8 (AN8)
1001 = Channel 9 (AN9)
1010 = Channel 10 (AN10)
1011 = Channel 11 (AN11)
1100 = Channel 12 (AN12)
1101 = Unimplemented(2)
1110 = Unimplemented(2)
1111 = Unimplemented(2)

bit 1 **GO/$\overline{\text{DONE}}$:** A/D Conversion Status bit
When ADON = 1:
1 = A/D conversion in progress
0 = A/D Idle

bit 0 **ADON:** A/D On bit
1 = A/D converter module is enabled
0 = A/D converter module is disabled

Note 1: These channels are not implemented on 28-pin devices.
2: Performing a conversion on unimplemented channels will return a floating input measurement.

REGISTER 21-2: ADCON1: A/D CONTROL REGISTER 1

U-0	U-0	R/W-0	R/W-0	R/W-0[(1)]	R/W[(1)]	R/W[(1)]	R/W[(1)]
—	—	VCFG0	VCFG0	PCFG3	PCFG2	PCFG1	PCFG0
bit 7							bit 0

Legend:			
R = Readable bit	W = Writable bit	U = Unimplemented bit, read as '0'	
-n = Value at POR	'1' = Bit is set	'0' = Bit is cleared	x = Bit is unknown

bit 7-6 **Unimplemented:** Read as '0'

bit 5 **VCFG0:** Voltage Reference Configuration bit (VREF- source)
1 = VREF- (AN2)
0 = VSS

bit 4 **VCFG0:** Voltage Reference Configuration bit (VREF+ source)
1 = VREF+ (AN3)
0 = VDD

bit 3-0 **PCFG3:PCFG0:** A/D Port Configuration Control bits:

PCFG3: PCFG0	AN12	AN11	AN10	AN9	AN8	AN7[(2)]	AN6[(2)]	AN5[(2)]	AN4	AN3	AN2	AN1	AN0
0000[(1)]	A	A	A	A	A	A	A	A	A	A	A	A	A
0001	A	A	A	A	A	A	A	A	A	A	A	A	A
0010	A	A	A	A	A	A	A	A	A	A	A	A	A
0011	D	A	A	A	A	A	A	A	A	A	A	A	A
0100	D	D	A	A	A	A	A	A	A	A	A	A	A
0101	D	D	D	A	A	A	A	A	A	A	A	A	A
0110	D	D	D	D	A	A	A	A	A	A	A	A	A
0111[(1)]	D	D	D	D	D	A	A	A	A	A	A	A	A
1000	D	D	D	D	D	D	A	A	A	A	A	A	A
1001	D	D	D	D	D	D	D	A	A	A	A	A	A
1010	D	D	D	D	D	D	D	D	A	A	A	A	A
1011	D	D	D	D	D	D	D	D	D	A	A	A	A
1100	D	D	D	D	D	D	D	D	D	D	A	A	A
1101	D	D	D	D	D	D	D	D	D	D	D	A	A
1110	D	D	D	D	D	D	D	D	D	D	D	D	A
1111	D	D	D	D	D	D	D	D	D	D	D	D	D

A = Analog input D = Digital I/O

Note 1: The POR value of the PCFG bits depends on the value of the PBADEN Configuration bit. When PBADEN = 1, PCFG<3:0> = 0000; when PBADEN = 0, PCFG<3:0> = 0111.

2: AN5 through AN7 are available only on 40/44-pin devices.

REGISTER 21-3: ADCON2: A/D CONTROL REGISTER 2

R/W-0	U-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
ADFM	—	ACQT2	ACQT1	ACQT0	ADCS2	ADCS1	ADCS0
bit 7							bit 0

Legend:			
R = Readable bit	W = Writable bit	U = Unimplemented bit, read as '0'	
-n = Value at POR	'1' = Bit is set	'0' = Bit is cleared	x = Bit is unknown

bit 7 **ADFM:** A/D Result Format Select bit
`1` = Right justified
`0` = Left justified

bit 6 **Unimplemented:** Read as '0'

bit 5-3 **ACQT2:ACQT0:** A/D Acquisition Time Select bits
`111` = 20 TAD
`110` = 16 TAD
`101` = 12 TAD
`100` = 8 TAD
`011` = 6 TAD
`010` = 4 TAD
`001` = 2 TAD
`000` = 0 TAD(1)

bit 2-0 **ADCS2:ADCS0:** A/D Conversion Clock Select bits
`111` = FRC (clock derived from A/D RC oscillator)(1)
`110` = FOSC/64
`101` = FOSC/16
`100` = FOSC/4
`011` = FRC (clock derived from A/D RC oscillator)(1)
`010` = FOSC/32
`001` = FOSC/8
`000` = FOSC/2

Note 1: If the A/D FRC clock source is selected, a delay of one TCY (instruction cycle) is added before the A/D clock starts. This allows the `SLEEP` instruction to be executed before starting a conversion.

The analog reference voltage is software selectable to either the device's positive and negative supply voltage (VDD and VSS) or the voltage level on the RA3/AN3/VREF+ and RA2/AN2/VREF-/CVREF pins.

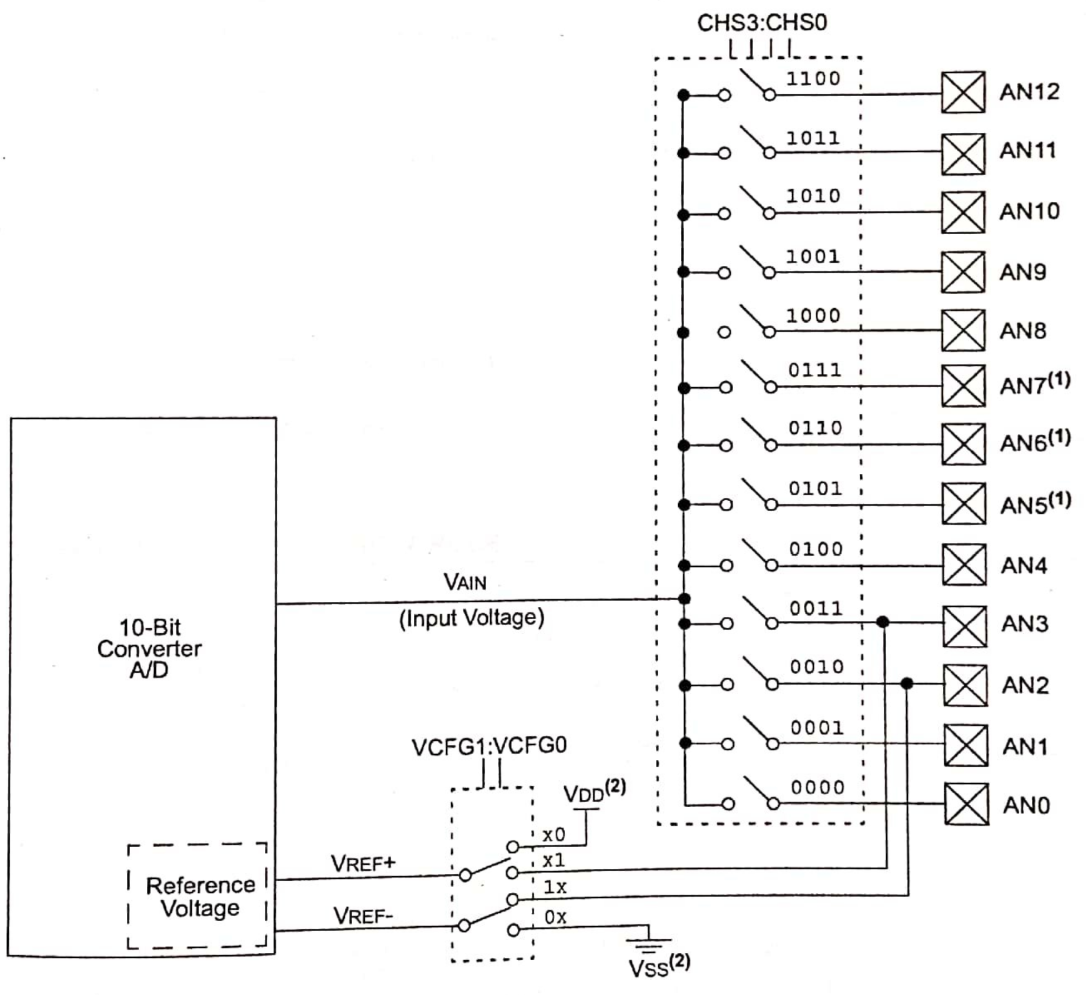
The A/D converter has a unique feature of being able to operate while the device is in Sleep mode. To operate in Sleep, the A/D conversion clock must be derived from the A/D's internal RC oscillator.

The output of the sample and hold is the input into the converter, which generates the result via successive approximation.

A device Reset forces all registers to their Reset state. This forces the A/D module to be turned off and any conversion in progress is aborted.

Each port pin associated with the A/D converter can be configured as an analog input or as a digital I/O. The ADRESH and ADRESL registers contain the result of the A/D conversion. When the A/D conversion is complete, the result is loaded into the ADRESH:ADRESL register pair, the GO/DONE bit (ADCON0 register) is cleared and A/D Interrupt Flag bit, ADIF, is set. The block diagram of the A/D module is shown in Figure 21-1.

FIGURE 21-1: A/D BLOCK DIAGRAM



Note 1: Channels AN5 through AN7 are not available on 28-pin devices.

2: I/O pins have diode protection to VDD and VSS.

Preliminary

The value in the ADRESH:ADRESL registers is not modified for a Power-on Reset. The ADRESH:ADRESL registers will contain unknown data after a Power-on Reset.

After the A/D module has been configured as desired, the selected channel must be acquired before the conversion is started. The analog input channels must have their corresponding TRIS bits selected as an input. To determine acquisition time, see **Section 21.1 "A/D Acquisition Requirements"**. After this acquisition time has elapsed, the A/D conversion can be started. An acquisition time can be programmed to occur between setting the GO/DONE bit and the actual start of the conversion.

The following steps should be followed to perform an A/D conversion:

1. Configure the A/D module:
   - Configure analog pins, voltage reference and digital I/O (ADCON1)
   - Select A/D input channel (ADCON0)
   - Select A/D acquisition time (ADCON2)
   - Select A/D conversion clock (ADCON2)
   - Turn on A/D module (ADCON0)
2. Configure A/D interrupt (if desired):
   - Clear ADIF bit
   - Set ADIE bit
   - Set GIE bit
3. Wait the required acquisition time (if required).
4. Start conversion:
   - Set GO/DONE bit (ADCON0 register)
5. Wait for A/D conversion to complete, by either:
   - Polling for the GO/DONE bit to be cleared

   OR
   - Waiting for the A/D interrupt
6. Read A/D Result registers (ADRESH:ADRESL); clear bit ADIF, if required.
7. For next conversion, go to step 1 or step 2, as required. The A/D conversion time per bit is defined as TAD. A minimum wait of 3 TAD is required before the next acquisition starts.

FIGURE 21-2: A/D TRANSFER FUNCTION

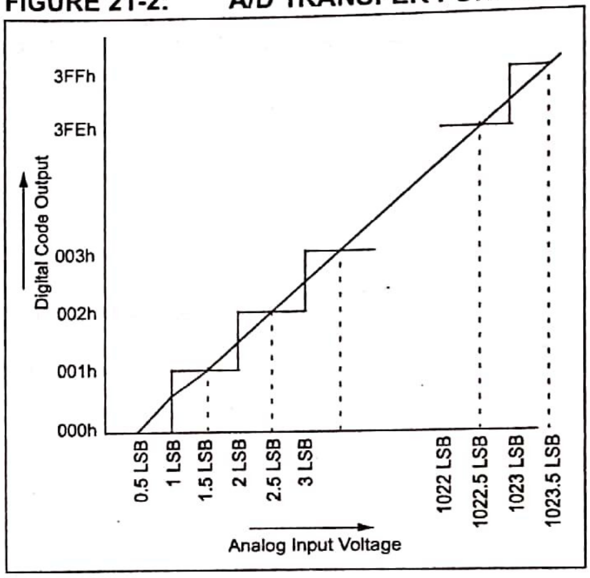
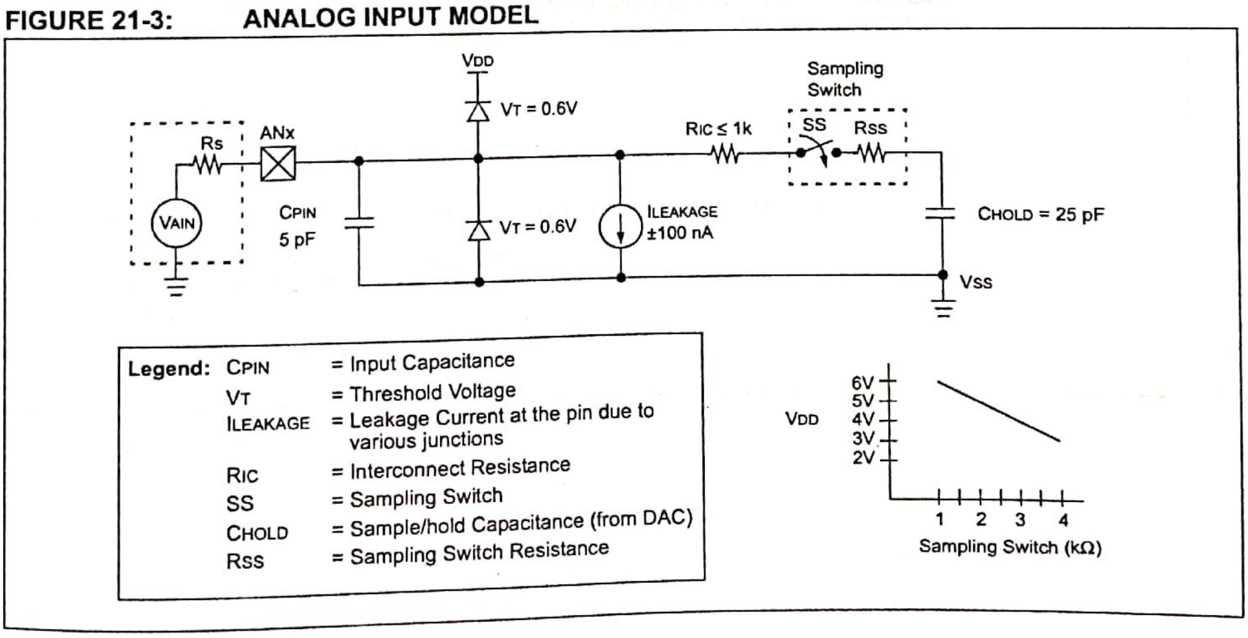


FIGURE 21-3: ANALOG INPUT MODEL



21.1 A/D Acquisition Requirements

For the A/D converter to meet its specified accuracy, the charge holding capacitor (CHOLD) must be allowed to fully charge to the input channel voltage level. The analog input model is shown in Figure 21-3. The source impedance (RS) and the internal sampling switch (RSS) impedance directly affect the time required to charge the capacitor CHOLD. The sampling switch (RSS) impedance varies over the device voltage (VDD). The source impedance affects the offset voltage at the analog input (due to pin leakage current). **The maximum recommended impedance for analog sources is 2.5 kΩ.** After the analog input channel is selected (changed), the channel must be sampled for at least the minimum acquisition time before starting a conversion.

Note:	When the conversion is started, the holding capacitor is disconnected from the input pin.

To calculate the minimum acquisition time, Equation 21-1 may be used. This equation assumes that 1/2 LSb error is used (1024 steps for the A/D). The 1/2 LSb error is the maximum error allowed for the A/D to meet its specified resolution.

Example 21-3 shows the calculation of the minimum required acquisition time TACQ. This calculation is based on the following application system assumptions:

CHOLD	=	25 pF
Rs	=	2.5 kΩ
Conversion Error	≤	1/2 LSb
VDD	=	5V → Rss = 2 kΩ
Temperature	=	85°C (system max.)

EQUATION 21-1: ACQUISITION TIME

$$T_{ACQ} = \text{Amplifier Settling Time} + \text{Holding Capacitor Charging Time} + \text{Temperature Coefficient}$$
$$= T_{AMP} + T_C + T_{COFF}$$

EQUATION 21-2: A/D MINIMUM CHARGING TIME

$$V_{HOLD} = (V_{REF} - (V_{REF}/2048)) \cdot (1 - e^{(-T_C/C_{HOLD}(R_{IC} + R_{SS} + R_S))})$$

or

$$T_C = -(C_{HOLD})(R_{IC} + R_{SS} + R_S)\ln(1/2048)$$

EQUATION 21-3: CALCULATING THE MINIMUM REQUIRED ACQUISITION TIME

$$T_{ACQ} = T_{AMP} + T_C + T_{COFF}$$

$$T_{AMP} = 0.2\ \mu s$$

$$T_{COFF} = (Temp - 25°C)(0.02\ \mu s/°C)$$
$$(85°C - 25°C)(0.02\ \mu s/°C)$$
$$1.2\ \mu s$$

Temperature coefficient is only required for temperatures > 25°C. Below 25°C, T_{COFF} = 0 ms.

$$T_C = -(C_{HOLD})(R_{IC} + R_{SS} + R_S)\ln(1/2048)\ \mu s$$
$$-(25\ pF)(1\ k\Omega + 2\ k\Omega + 2.5\ k\Omega)\ln(0.0004883)\ \mu s$$
$$1.05\ \mu s$$

$$T_{ACQ} = 0.2\ \mu s + 1.05\ \mu s + 1.2\ \mu s$$
$$2.45\ \mu s$$

21.2 Selecting and Configuring Acquisition Time

The ADCON2 register allows the user to select an acquisition time that occurs each time the GO/$\overline{DONE}$ bit is set. It also gives users the option to use an automatically determined acquisition time.

Acquisition time may be set with the ACQT2:ACQT0 bits (ADCON2<5:3>) which provide a range of 2 to 20 TAD. When the GO/$\overline{DONE}$ bit is set, the A/D module continues to sample the input for the selected acquisition time, then automatically begins a conversion. Since the acquisition time is programmed, there may be no need to wait for an acquisition time between selecting a channel and setting the GO/$\overline{DONE}$ bit.

Manual acquisition is selected when ACQT2:ACQT0 = `000`. When the GO/$\overline{DONE}$ bit is set, sampling is stopped and a conversion begins. The user is responsible for ensuring the required acquisition time has passed between selecting the desired input channel and setting the GO/$\overline{DONE}$ bit. This option is also the default Reset state of the ACQT2:ACQT0 bits and is compatible with devices that do not offer programmable acquisition times.

In either case, when the conversion is completed, the GO/$\overline{DONE}$ bit is cleared, the ADIF flag is set and the A/D begins sampling the currently selected channel again. If an acquisition time is programmed, there is nothing to indicate if the acquisition time has ended or if the conversion has begun.

21.3 Selecting the A/D Conversion Clock

The A/D conversion time per bit is defined as TAD. The A/D conversion requires 11 TAD per 10-bit conversion. The source of the A/D conversion clock is software selectable. There are seven possible options for TAD:

- 2 TOSC
- 4 TOSC
- 8 TOSC
- 16 TOSC
- 32 TOSC
- 64 TOSC
- Internal RC Oscillator

For correct A/D conversions, the A/D conversion clock (TAD) must be as short as possible but greater than the minimum TAD (see parameter 130 in Table 28-29 for more information).

Table 21-1 shows the resultant TAD times derived from the device operating frequencies and the A/D clock source selected.

TABLE 21-1: TAD vs. DEVICE OPERATING FREQUENCIES

AD Clock Source (TAD)		Maximum Device Frequency	
Operation	**ADCS2:ADCS0**	**PIC18FXXXX**	**PIC18LFXXXX[(4)]**
2 TOSC	`000`	2.86 MHz	1.43 MHz
4 TOSC	`100`	5.71 MHz	2.86 MHz
8 TOSC	`001`	11.43 MHz	5.72 MHz
16 TOSC	`101`	22.86 MHz	11.43 MHz
32 TOSC	`010`	45.71 MHz	22.86 MHz
64 TOSC	`110`	48.0 MHz	45.71 MHz
RC[(3)]	`x11`	1.00 MHz[(1)]	1.00 MHz[(2)]

Note 1: The RC source has a typical TAD time of 4 ms.
2: The RC source has a typical TAD time of 6 ms.
3: For device frequencies above 1 MHz, the device must be in Sleep for the entire conversion or the A/D accuracy may be out of specification.
4: Low-power devices only.

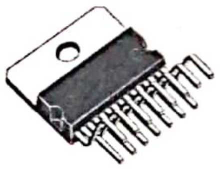
Appendix (F)

L298N H-Bridge

L298

DUAL FULL-BRIDGE DRIVER

- OPERATING SUPPLY VOLTAGE UP TO 46 V
- TOTAL DC CURRENT UP TO 4 A
- LOW SATURATION VOLTAGE
- OVERTEMPERATURE PROTECTION
- LOGICAL "0" INPUT VOLTAGE UP TO 1.5 V (HIGH NOISE IMMUNITY)


Multiwatt15

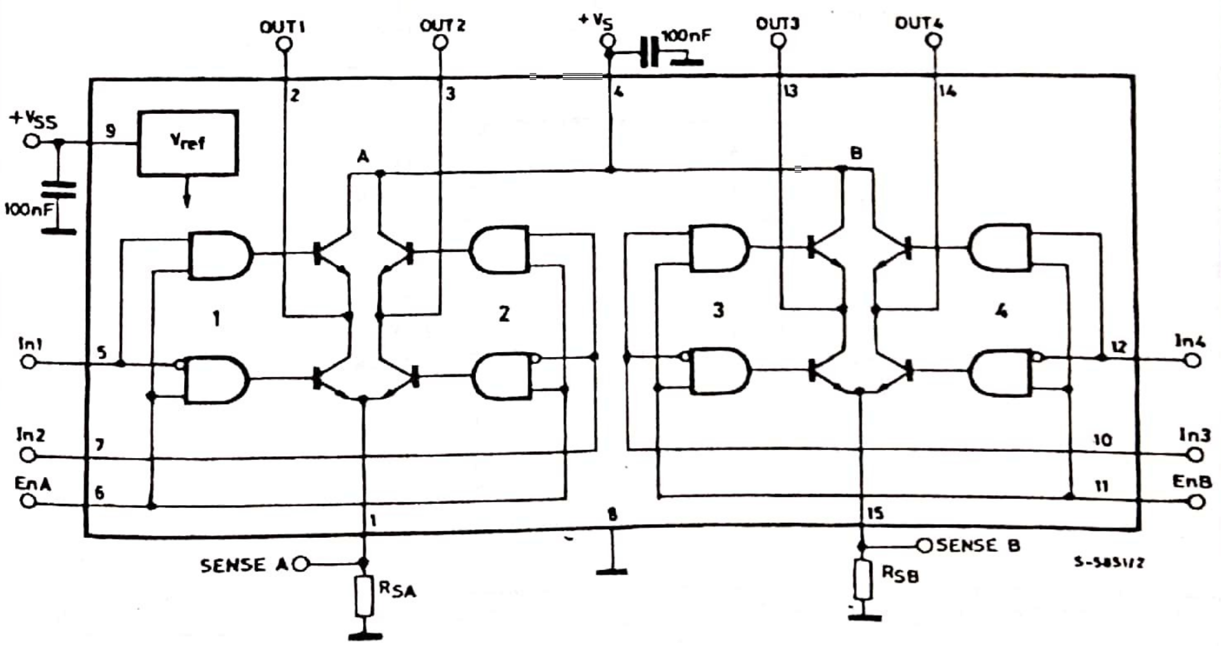

PowerSO20

ORDERING NUMBERS : L298N (Multiwatt Vert.)
L298HN (Multiwatt Horiz.)
L298P (PowerSO20)

DESCRIPTION

The L298 is an integrated monolithic circuit in a 15-lead Multiwatt and PowerSO20 packages. It is a high voltage, high current dual full-bridge driver designed to accept standard TTL logic levels and drive inductive loads such as relays, solenoids, DC and stepping motors. Two enable inputs are provided to enable or disable the device independently of the input signals. The emitters of the lower transistors of each bridge are connected together and the corresponding external terminal can be used for the connection of an external sensing resistor. An additional supply input is provided so that the logic works at a lower voltage.

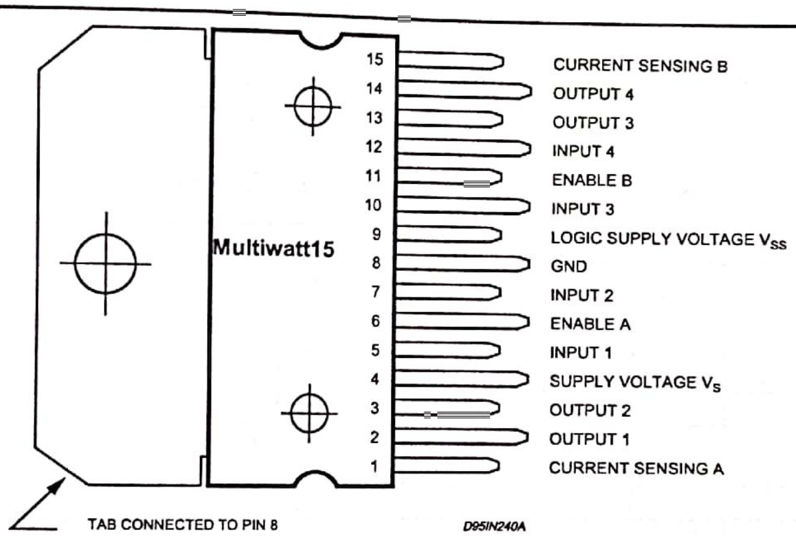
BLOCK DIAGRAM

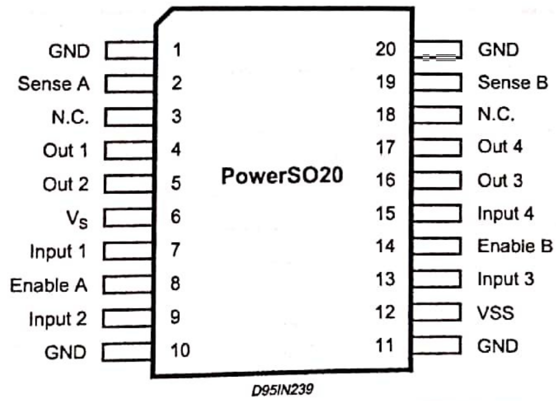


ABSOLUTE MAXIMUM RATINGS

Symbol	Parameter	Value	Unit
V_S	Power Supply	50	V
V_{SS}	Logic Supply Voltage	7	V
V_I,V_{en}	Input and Enable Voltage	–0.3 to 7	V
I_O	Peak Output Current (each Channel) – Non Repetitive (t = 100µs) –Repetitive (80% on –20% off; t_{on} = 10ms) –DC Operation	 3 2.5 2	 A A A
V_{sens}	Sensing Voltage	–1 to 2.3	V
P_{tot}	Total Power Dissipation (T_{case} = 75°C)	25	W
T_{op}	Junction Operating Temperature	–25 to 130	°C
T_{stg}, T_j	Storage and Junction Temperature	–40 to 150	°C

PIN CONNECTIONS (top view)





THERMAL DATA

Symbol	Parameter		PowerSO20	Multiwatt15	Unit
$R_{th\ j\text{-}case}$	Thermal Resistance Junction-case	Max.	–	3	°C/W
$R_{th\ j\text{-}amb}$	Thermal Resistance Junction-ambient	Max.	13 (*)	35	°C/W

(*) Mounted on aluminum substrate

PIN FUNCTIONS (refer to the block diagram)

MW.15	PowerSO	Name	Function
1;15	2;19	Sense A; Sense B	Between this pin and ground is connected the sense resistor to control the current of the load.
2;3	4;5	Out 1; Out 2	Outputs of the Bridge A; the current that flows through the load connected between these two pins is monitored at pin 1.
4	6	V_S	Supply Voltage for the Power Output Stages. A non-inductive 100nF capacitor must be connected between this pin and ground.
5;7	7;9	Input 1; Input 2	TTL Compatible Inputs of the Bridge A.
6;11	8;14	Enable A; Enable B	TTL Compatible Enable Input: the L state disables the bridge A (enable A) and/or the bridge B (enable B).
8	1,10,11,20	GND	Ground.
9	12	VSS	Supply Voltage for the Logic Blocks. A100nF capacitor must be connected between this pin and ground.
10; 12	13;15	Input 3; Input 4	TTL Compatible Inputs of the Bridge B.
13; 14	16;17	Out 3; Out 4	Outputs of the Bridge B. The current that flows through the load connected between these two pins is monitored at pin 15.
–	3;18	N.C.	Not Connected

ELECTRICAL CHARACTERISTICS (V_S = 42V; V_{SS} = 5V, T_j = 25°C; unless otherwise specified)

Symbol	Parameter	Test Conditions		Min.	Typ.	Max.	Unit
V_S	Supply Voltage (pin 4)	Operative Condition		V_{IH} +2.5		46	V
V_{SS}	Logic Supply Voltage (pin 9)			4.5	5	7	V
I_S	Quiescent Supply Current (pin 4)	V_{en} = H; I_L = 0	V_i = L V_i = H		13 50	22 70	mA mA
		V_{en} = L	V_i = X			4	mA
I_{SS}	Quiescent Current from V_{SS} (pin 9)	V_{en} = H; I_L = 0	V_i = L V_i = H		24 7	36 12	mA mA
		V_{en} = L	V_i = X			6	mA
V_{iL}	Input Low Voltage (pins 5, 7, 10, 12)			–0.3		1.5	V
V_{iH}	Input High Voltage (pins 5, 7, 10, 12)			2.3		VSS	V
I_{iL}	Low Voltage Input Current (pins 5, 7, 10, 12)	V_i = L				–10	μA
I_{iH}	High Voltage Input Current (pins 5, 7, 10, 12)	Vi = H ≤ V_{SS} –0.6V			30	100	μA
V_{en} = L	Enable Low Voltage (pins 6, 11)			–0.3		1.5	V
V_{en} = H	Enable High Voltage (pins 6, 11)			2.3		V_{SS}	V
I_{en} = L	Low Voltage Enable Current (pins 6, 11)	V_{en} = L				–10	μA
I_{en} = H	High Voltage Enable Current (pins 6, 11)	V_{en} = H ≤ V_{SS} –0.6V			30	100	μA
$V_{CEsat (H)}$	Source Saturation Voltage	I_L = 1A I_L = 2A		0.95	1.35 2	1.7 2.7	V V
$V_{CEsat (L)}$	Sink Saturation Voltage	I_L = 1A (5) I_L = 2A (5)		0.85	1.2 1.7	1.6 2.3	V V
V_{CEsat}	Total Drop	I_L = 1A (5) I_L = 2A (5)		1.80		3.2 4.9	V V
V_{sens}	Sensing Voltage (pins 1, 15)			–1 (1)		2	V

ELECTRICAL CHARACTERISTICS (continued)

Symbol	Parameter	Test Conditions	Min.	Typ.	Max.	Unit
T_1 (V_i)	Source Current Turn-off Delay	0.5 V_i to 0.9 I_L (2); (4)		1.5		µs
T_2 (V_i)	Source Current Fall Time	0.9 I_L to 0.1 I_L (2); (4)		0.2		µs
T_3 (V_i)	Source Current Turn-on Delay	0.5 V_i to 0.1 I_L (2); (4)		2		µs
T_4 (V_i)	Source Current Rise Time	0.1 I_L to 0.9 I_L (2); (4)		0.7		µs
T_5 (V_i)	Sink Current Turn-off Delay	0.5 V_i to 0.9 I_L (3); (4)		0.7		µs
T_6 (V_i)	Sink Current Fall Time	0.9 I_L to 0.1 I_L (3); (4)		0.25		µs
T_7 (V_i)	Sink Current Turn-on Delay	0.5 V_i to 0.9 I_L (3); (4)		1.6		µs
T_8 (V_i)	Sink Current Rise Time	0.1 I_L to 0.9 I_L (3); (4)		0.2		µs
fc (V_i)	Commutation Frequency	I_L = 2A		25	40	KHz
T_1 (V_{en})	Source Current Turn-off Delay	0.5 V_{en} to 0.9 I_L (2); (4)		3		µs
T_2 (V_{en})	Source Current Fall Time	0.9 I_L to 0.1 I_L (2); (4)		1		µs
T_3 (V_{en})	Source Current Turn-on Delay	0.5 V_{en} to 0.1 I_L (2); (4)		0.3		µs
T_4 (V_{en})	Source Current Rise Time	0.1 I_L to 0.9 I_L (2); (4)		0.4		µs
T_5 (V_{en})	Sink Current Turn-off Delay	0.5 V_{en} to 0.9 I_L (3); (4)		2.2		µs
T_6 (V_{en})	Sink Current Fall Time	0.9 I_L to 0.1 I_L (3); (4)		0.35		µs
T_7 (V_{en})	Sink Current Turn-on Delay	0.5 V_{en} to 0.9 I_L (3); (4)		0.25		µs
T_8 (V_{en})	Sink Current Rise Time	0.1 I_L to 0.9 I_L (3); (4)		0.1		µs

1) 1)Sensing voltage can be –1 V for t ≤ 50 µsec; in steady state V_{sens} min ≥ – 0.5 V.
2) See fig. 2.
3) See fig. 4.
4) The load must be a pure resistor.

Figure 1 : Typical Saturation Voltage vs. Output Current.

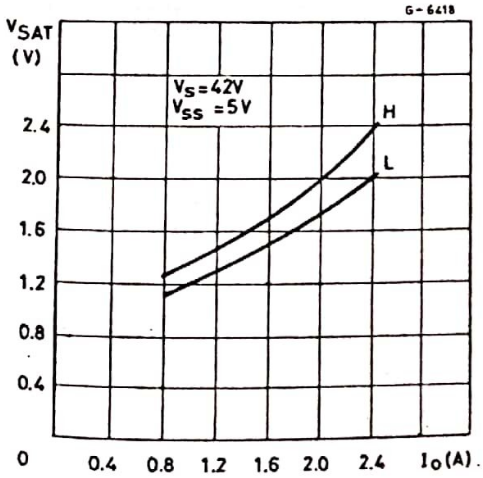
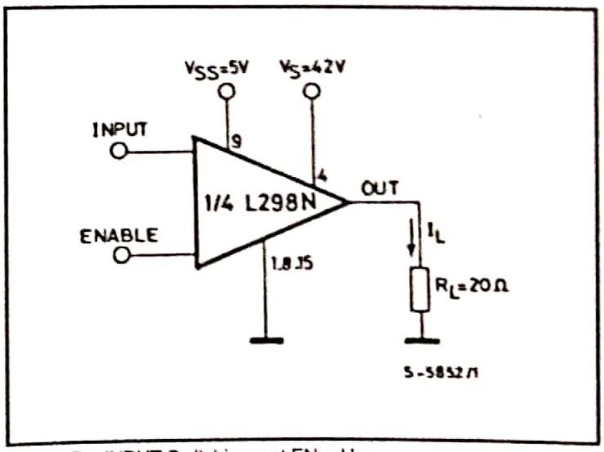


Figure 2 : Switching Times Test Circuits.



Note : For INPUT Switching, set EN = H
For ENABLE Switching, set IN = H

Figure 3 : Source Current Delay Times vs. Input or Enable Switching.

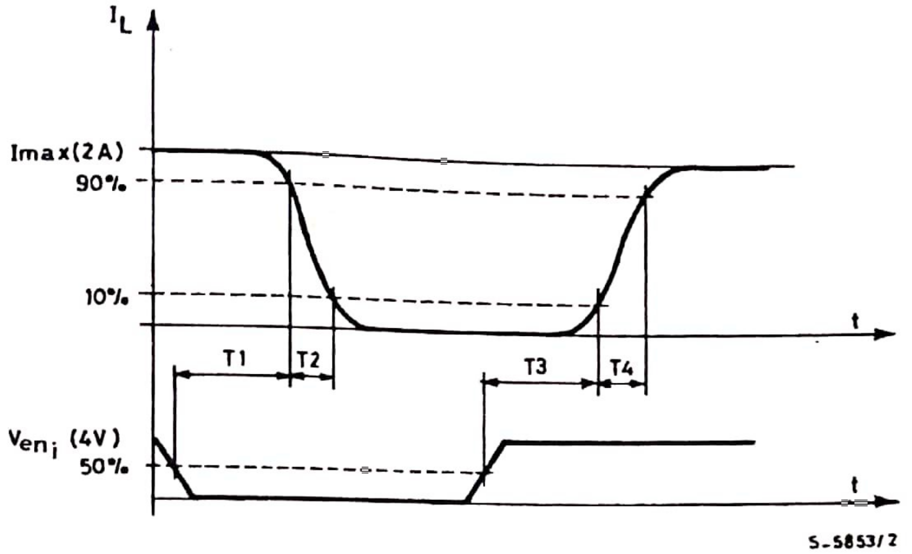
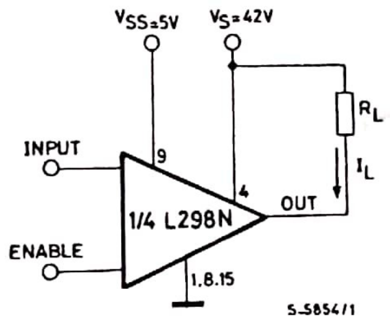


Figure 4 : Switching Times Test Circuits.



Note : For INPUT Switching, set EN = H
For ENABLE Switching, set IN = L

Figure 5 : Sink Current Delay Times vs. Input 0 V Enable Switching.

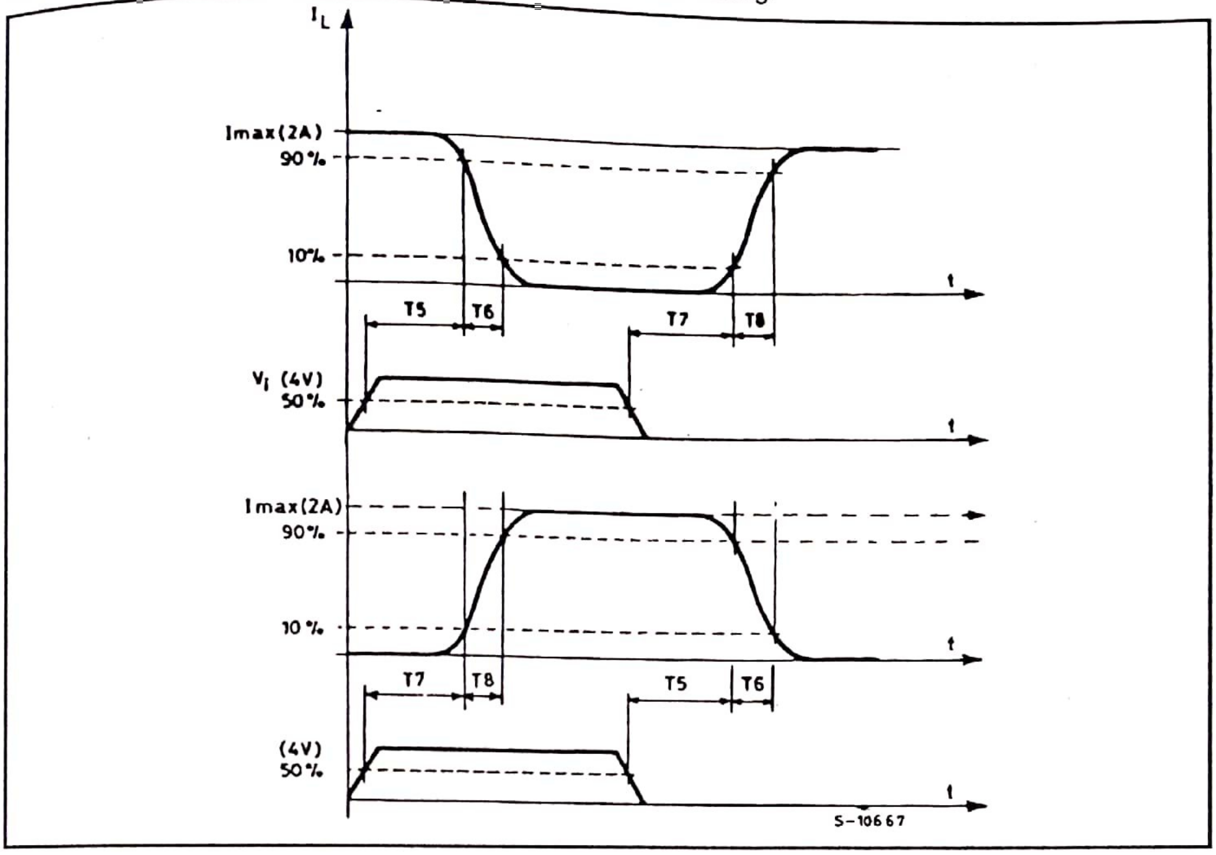
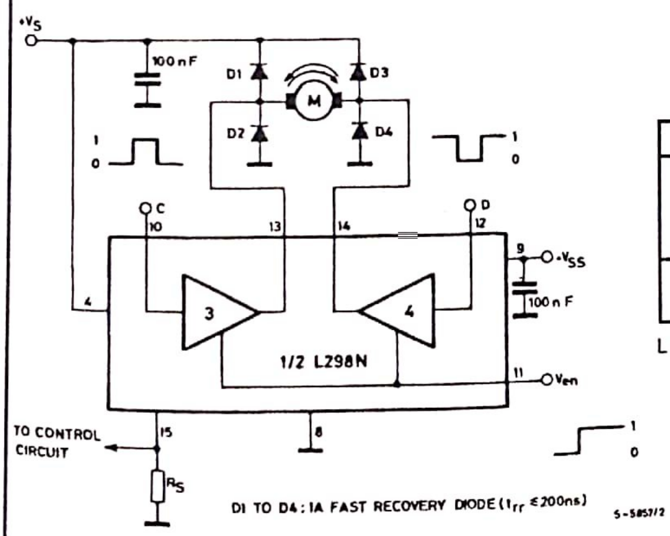


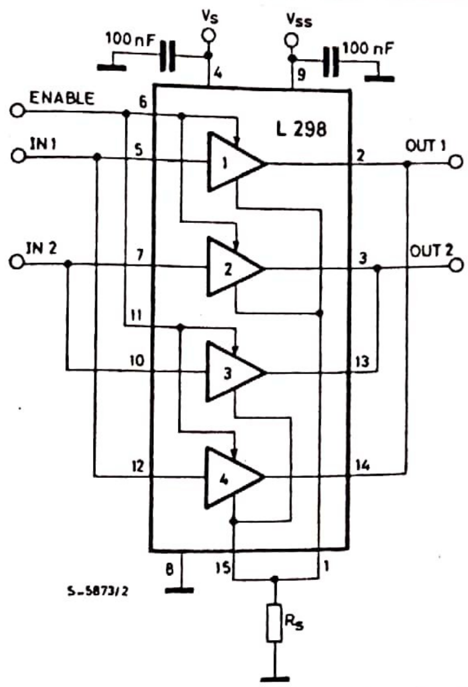
Figure 6 : Bidirectional DC Motor Control.



Inputs		Function
V_{en} = H	C = H ; D = L	Forward
	C = L ; D = H	Reverse
	C = D	Fast Motor Stop
V_{en} = L	C = X ; D = X	Free Running Motor Stop

L = Low H = High X = Don't care

Figure 7 : For higher currents, outputs can be paralleled. Take care to parallel channel 1 with channel 4 and channel 2 with channel 3.



APPLICATION INFORMATION (Refer to the block diagram)

1.1. POWER OUTPUT STAGE

The L298 integrates two power output stages (A ; B). The power output stage is a bridge configuration and its outputs can drive an inductive load in common or differenzial mode, depending on the state of the inputs. The current that flows through the load comes out from the bridge at the sense output : an external resistor (R_{SA} ; R_{SB}.) allows to detect the intensity of this current.

1.2. INPUT STAGE

Each bridge is driven by means of four gates the input of which are In1 ; In2 ; EnA and In3 ; In4 ; EnB. The In inputs set the bridge state when The En input is high ; a low state of the En input inhibits the bridge. All the inputs are TTL compatible.

2. SUGGESTIONS

A non inductive capacitor, usually of 100 nF, must be foreseen between both Vs and Vss, to ground, as near as possible to GND pin. When the large capacitor of the power supply is too far from the IC, a second smaller one must be foreseen near the L298.

The sense resistor, not of a wire wound type, must be grounded near the negative pole of Vs that must be near the GND pin of the I.C.

Each input must be connected to the source of the driving signals by means of a very short path.

Turn-On and Turn-Off : Before to Turn-ON the Supply Voltage and before to Turn it OFF, the Enable input must be driven to the Low state.

3. APPLICATIONS

Fig 6 shows a bidirectional DC motor control Schematic Diagram for which only one bridge is needed. The external bridge of diodes D1 to D4 is made by four fast recovery elements ($t_{rr} \leq 200$ nsec) that must be chosen of a VF as low as possible at the worst case of the load current.

The sense output voltage can be used to control the current amplitude by chopping the inputs, or to provide overcurrent protection by switching low the enable input.

The brake function (Fast motor stop) requires that the Absolute Maximum Rating of 2 Amps must never be overcome.

When the repetitive peak current needed from the load is higher than 2 Amps, a paralleled configuration can be chosen (See Fig.7).

An external bridge of diodes are required when inductive loads are driven and when the inputs of the IC are chopped ; Shottky diodes would be preferred.

This solution can drive until 3 Amps In DC operation and until 3.5 Amps of a repetitive peak current.

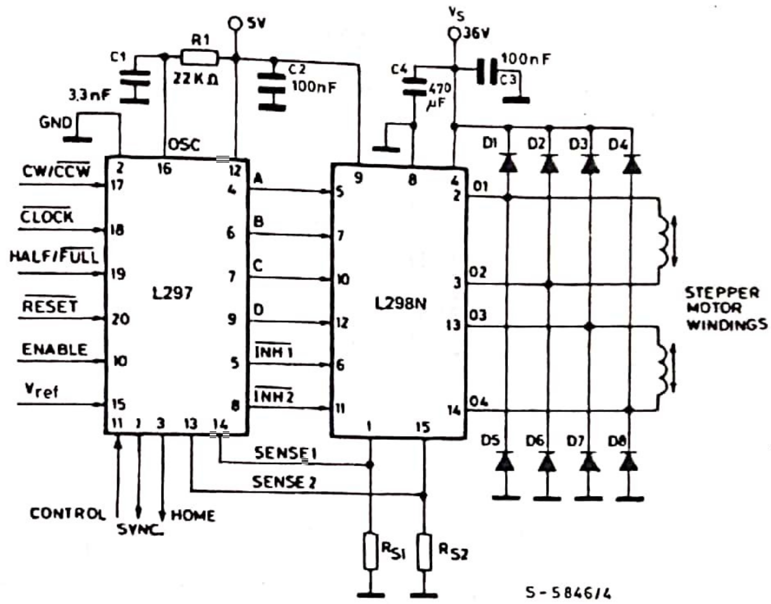
On Fig 8 it is shown the driving of a two phase bipolar stepper motor ; the needed signals to drive the inputs of the L298 are generated, in this example, from the IC L297.

Fig 9 shows an example of P.C.B. designed for the application of Fig 8.

Fig 10 shows a second two phase bipolar stepper motor control circuit where the current is controlled by the I.C. L6506.

Figure 8 : Two Phase Bipolar Stepper Motor Circuit.

This circuit drives bipolar stepper motors with winding currents up to 2 A. The diodes are fast 2 A types.



$R_{S1} = R_{S2} = 0.5\ \Omega$

D1 to D8 = 2 A Fast diodes { $V_F \leq 1.2$ V @ I = 2 A; $t_{rr} \leq 200$ ns }

Figure 9 : Suggested Printed Circuit Board Layout for the Circuit of fig. 8 (1:1 scale).

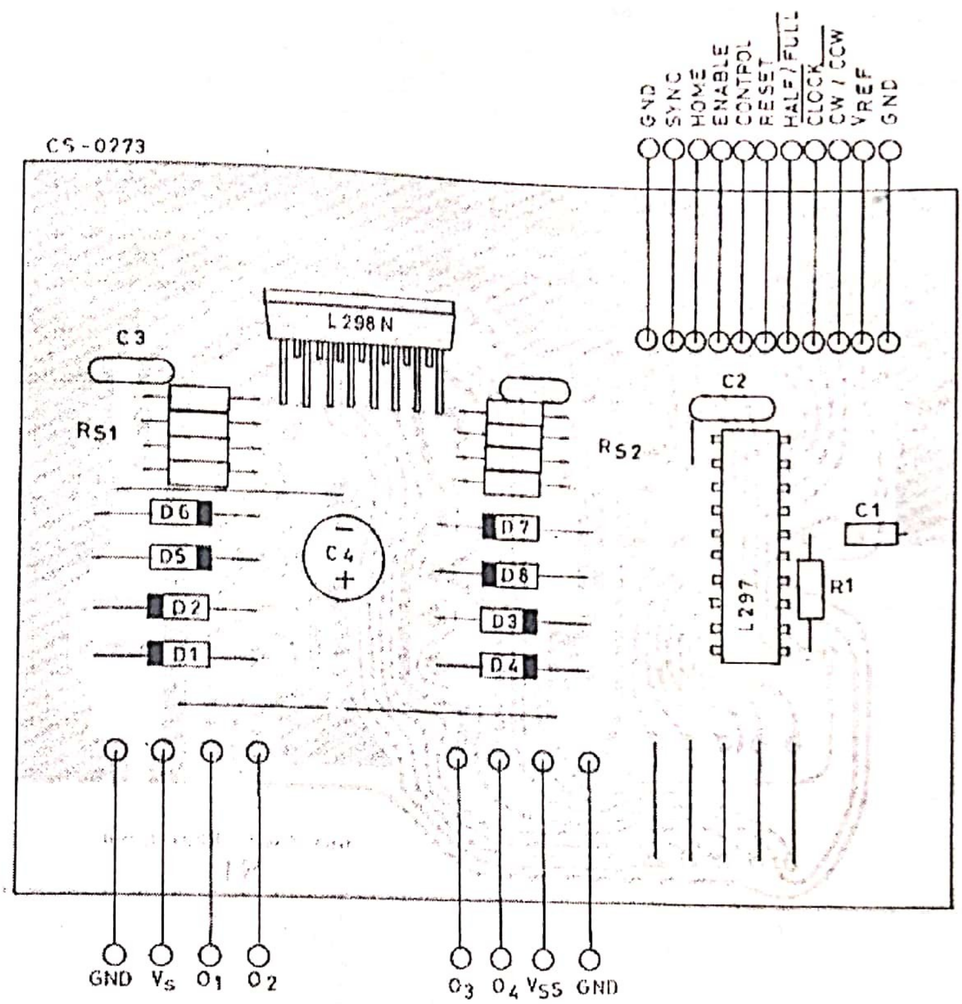
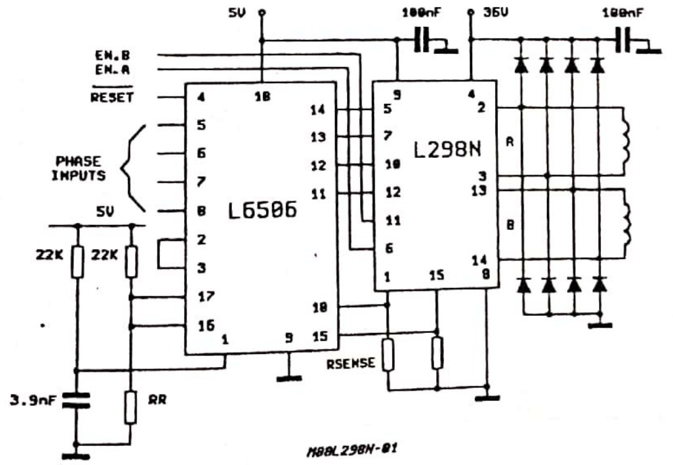


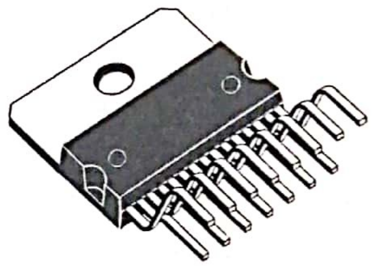
Figure 10 : Two Phase Bipolar Stepper Motor Control Circuit by Using the Current Controller L6506.



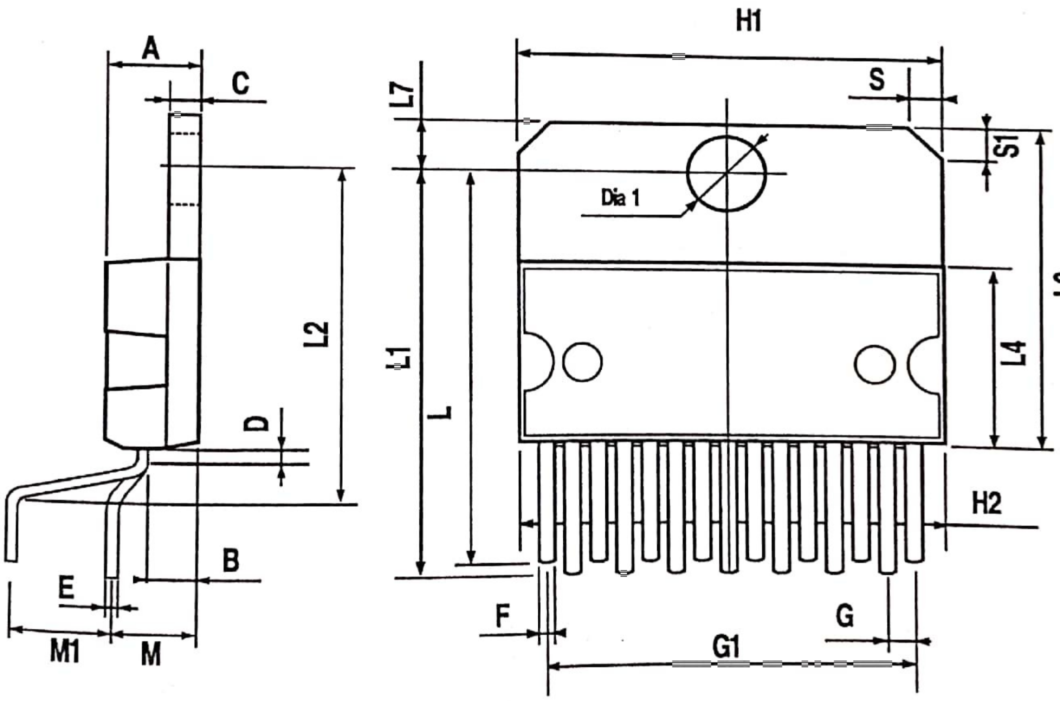
R_R and R_{sense} depend from the load current

DIM.	mm			inch		
	MIN.	TYP.	MAX.	MIN.	TYP.	MAX.
A			5			0.197
B			2.65			0.104
C			1.6			0.063
D		1			0.039	
E	0.49		0.55	0.019		0.022
F	0.66		0.75	0.026		0.030
G	1.02	1.27	1.52	0.040	0.050	0.060
G1	17.53	17.78	18.03	0.690	0.700	0.710
H1	19.6			0.772		
H2			20.2			0.795
L	21.9	22.2	22.5	0.862	0.874	0.886
L1	21.7	22.1	22.5	0.854	0.870	0.886
L2	17.65		18.1	0.695		0.713
L3	17.25	17.5	17.75	0.679	0.689	0.699
L4	10.3	10.7	10.9	0.406	0.421	0.429
L7	2.65		2.9	0.104		0.114
M	4.25	4.55	4.85	0.167	0.179	0.191
M1	4.63	5.08	5.53	0.182	0.200	0.218
S	1.9		2.6	0.075		0.102
S1	1.9		2.6	0.075		0.102
Dia1	3.65		3.85	0.144		0.152

OUTLINE AND MECHANICAL DATA

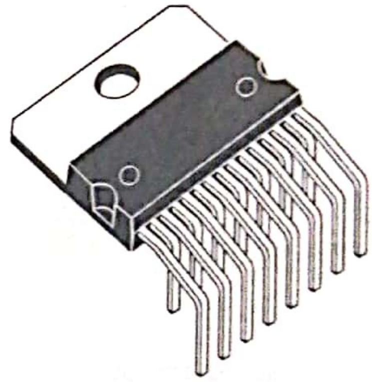


Multiwatt15 V

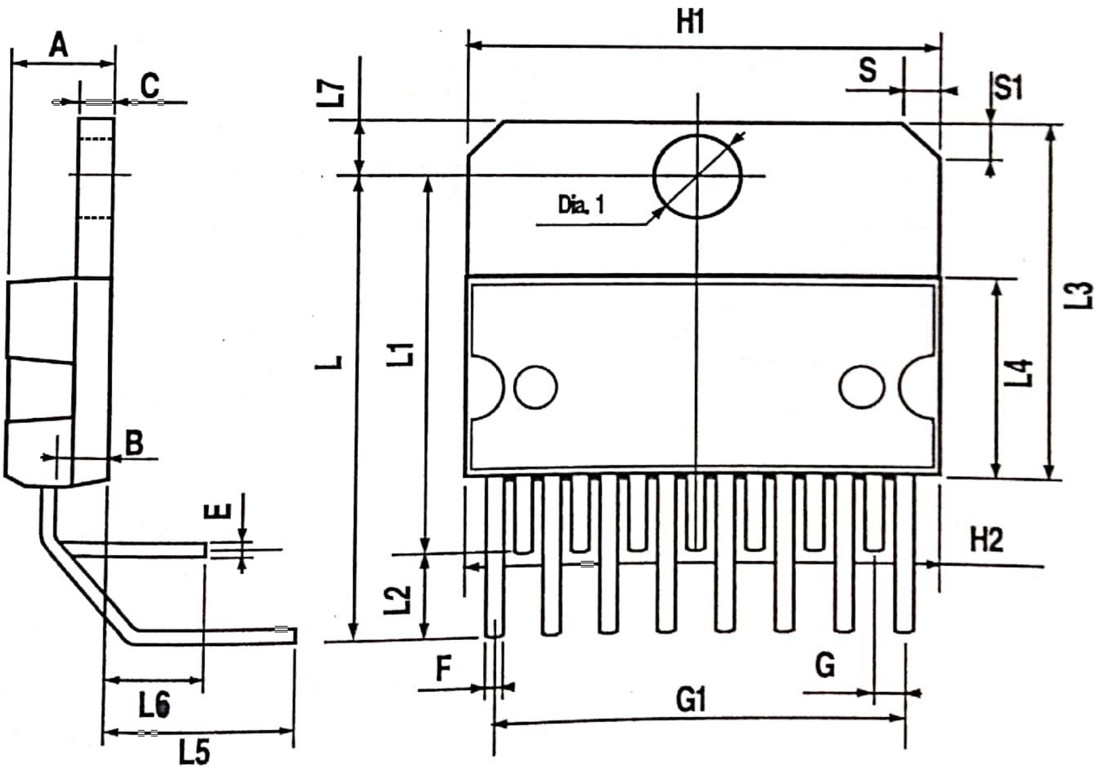


DIM.	mm			inch		
	MIN.	TYP.	MAX.	MIN.	TYP.	MAX.
A			5			0.197
B			2.65			0.104
C			1.6			0.063
E	0.49		0.55	0.019		0.022
F	0.66		0.75	0.026		0.030
G	1.14	1.27	1.4	0.045	0.050	0.055
G1	17.57	17.78	17.91	0.692	0.700	0.705
H1	19.6			0.772		
H2			20.2			0.795
L		20.57			0.810	
L1		18.03			0.710	
L2		2.54			0.100	
L3	17.25	17.5	17.75	0.679	0.689	0.699
L4	10.3	10.7	10.9	0.406	0.421	0.429
L5		5.28			0.208	
L6		2.38			0.094	
L7	2.65		2.9	0.104		0.114
S	1.9		2.6	0.075		0.102
S1	1.9		2.6	0.075		0.102
Dia1	3.65		3.85	0.144		0.152

OUTLINE AND MECHANICAL DATA



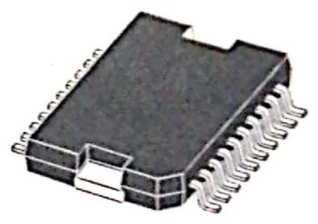
Multiwatt15 H



DIM.	mm			inch		
	MIN.	TYP.	MAX.	MIN.	TYP.	MAX.
A			3.6			0.142
a1	0.1		0.3	0.004		0.012
a2			3.3			0.130
a3	0		0.1	0.000		0.004
b	0.4		0.53	0.016		0.021
c	0.23		0.32	0.009		0.013
D (1)	15.8		16	0.622		0.630
D1	9.4		9.8	0.370		0.386
E	13.9		14.5	0.547		0.570
e		1.27			0.050	
e3		11.43			0.450	
E1 (1)	10.9		11.1	0.429		0.437
E2			2.9			0.114
E3	5.8		6.2	0.228		0.244
G	0		0.1	0.000		0.004
H	15.5		15.9	0.610		0.626
h			1.1			0.043
L	0.8		1.1	0.031		0.043
N	10° (max.)					
S	8° (max.)					
T		10			0.394	

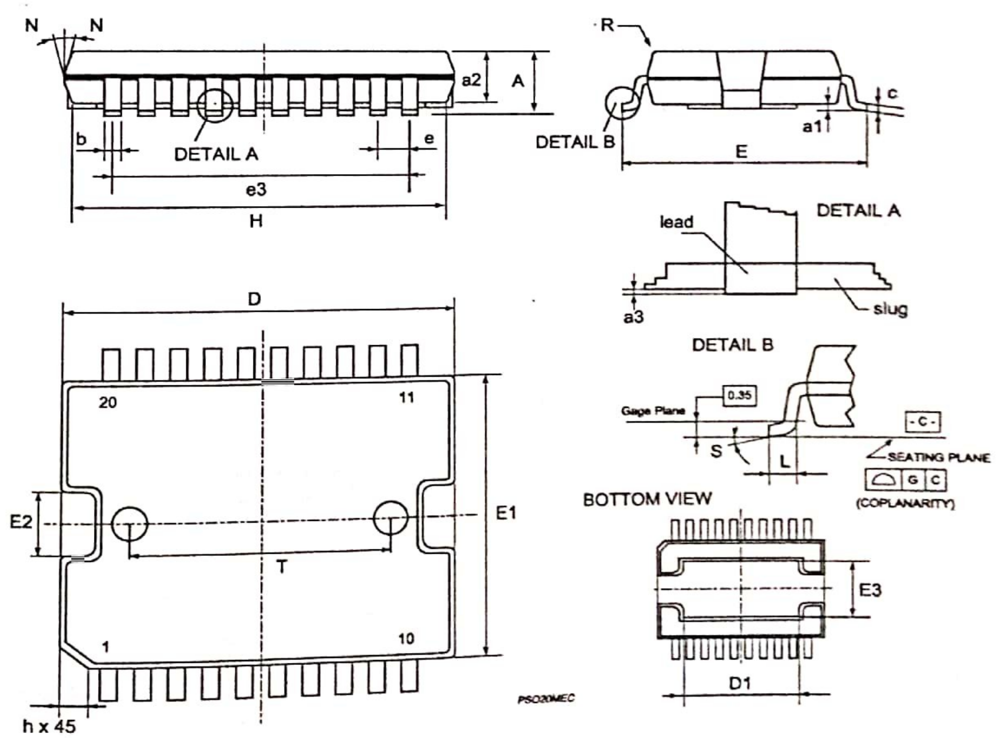
(1) "D and F" do not include mold flash or protrusions.
- Mold flash or protrusions shall not exceed 0.15 mm (0.006").
- Critical dimensions: "E", "G" and "a3"

OUTLINE AND MECHANICAL DATA



JEDEC MO-166

PowerSO20



Appendix (G) Programming code of PIC

```
#include <p18f4550.h>

#include <adc.h>

#include<pwm.h>

#include<delays.h>

#include<timers.h>

float Sone=0,Stwo=0,SLeft=0,Sright=0;

float X,ek,ek_1=0,ek_2=0,uk=0,uk_1=0,kp=1000,ki=400,T=0.01;

#pragma config FOSC = INTOSC_HS

#pragma config WDT = OFF

#pragma config LVP = OFF

void main( void)

{

OpenADC(ADC_FOSC_64 & ADC_RIGHT_JUST & ADC_2_TAD, ADC_INT_OFF &
ADC_REF_VDD_VSS, ADC_4ANA ); // use 4 analog inputs AN0 to AN3

OpenTimer2(T2_PS_1_1 & TIMER_INT_OFF);    // prescalar 1 to make the frequency 20 Khz

OpenTimer3(TIMER_INT_ON & T3_16BIT_RW
&T3_SOURCE_INT&T3_PS_1_2&T3_SYNC_EXT_OFF);

TRISE=0;                      // use port E for output for logic enables of H bridge

TRISC=0;                      // Set portC for PWM outputs.

INTCON=0b11000000;

PIE2=0b00000010;

PIR2=0b00000000;

OSCCON=0xff;

ADCON1=0b00001011;

OpenPWM1(99);          // set period (0x00 to oxff) to 100 to get 20 KHz where
(100)*4*(1/8)*10^-6*(1(prescalar))=5*10-5(20 kHZ)

OpenPWM2(99);

SetDCPWM1(0);

SetDCPWM2(0);
```

```
WriteTimer3(45535);


********************//start the infint loop****************************

while(1)

   {

************* //    start comparing*******************


***********************//case 2 sensor 2 is > than sensor 1 *********************************

  if((SLeft-Sright)>0.3)   // check if difference between them is larger than 0.5 V

{

     ek=SLeft-Sright;              // error signal

     uk=uk_1+(kp+(ki*T/2))*ek+(-kp+(ki*T/2))*ek_1;   //PID of the error signal contain only
P&I elements

     X=400/uk;

     while(1)

     {

     ek=SLeft-Sright;              // error signal

     uk=uk_1+(kp+(ki*T/2))*ek+(-kp+(ki*T/2))*ek_1;   //PID of the error signal contain only
P&I elements

     uk_1=uk;                    //previous error signal

     ek_1=ek;

     PORTE=0x01;                  // enable motor 1

     SetDCPWM2(0);                 // turn off the other direction

     SetDCPWM1(X*uk);                   //change duty cycle based on changes in output


      if((SLeft-Sright)<0.05)  // if the voltage difference is less than 0.05 V

   {

     SetDCPWM1(0);        // turn off the motor
```

```
        uk_1=0;            //in order to start new control loop again from the beginning

        ek_1=0;

       break;            //get out of loop

        }

       }

       } // for the first if condition


**********************//case 2 sensor 2 is > than sensor 1 ********************************

   if((Sright-Sleft)>0.3)    // check if difference between them is larger than 0.5 V

{

       ek= Sright-Sleft;            // error signal

       uk=uk_1+(kp+(ki*T/2))*ek+(-kp+(ki*T/2))*ek_1;   //PID of the error signal contain only
P&I elements

       X=400/uk;

       while(1)

       {

       ek= Sright-Sleft;            // error signal

       uk=uk_1+(kp+(ki*T/2))*ek+(-kp+(ki*T/2))*ek_1;   //PID of the error signal contain only
P&I elements

       uk_1=uk;                 //previous error signal

       ek_1=ek;

       PORTE=0x01;              // enable motor 1

       SetDCPWM1(0);              // turn off the other direction

       SetDCPWM2(X*uk);                //change duty cycle based on changes in output


       if((Sright-Sleft)<0.05)  // if the voltage difference is less than 0.05 V

      {

       SetDCPWM2(0);        // turn off the motor
```

```
    uk_1=0;            //in order to start new control loop again from the beginning

    ek_1=0;

   break;            //get out of loop

    }

   }

   } // for the first if condition

if(((Sright-SLeft)<0.05)||((SLeft-Sright)<0.05((

{

******************/case 3 sensor 3 is > than sensor 4*******************************

  if((Sone-Stwo)>0.3)   // check if difference between them is larger than 0.5 V

{

     ek= Sone-Stwo;          // error signal

     uk=uk_1+(kp+(ki*T/2))*ek+(-kp+(ki*T/2))*ek_1;   //PID of the error signal contain only
P&I elements   .

     X=400/uk;

     while(1)

     {

     ek= Sone-Stwo;          // error signal

     uk=uk_1+(kp+(ki*T/2))*ek+(-kp+(ki*T/2))*ek_1;   //PID of the error signal contain only
P&I elements

     uk_1=uk;            //previous error signal

     ek_1=ek;

     PORTE=0x02;           // enable motor 1

     SetDCPWM2(0);           // turn off the other direction

     SetDCPWM1(X*uk);             //change duty cycle based on changes in output
```

```
if((Sone-Stwo)<0.05)  // if the voltage difference is less than 0.05 V
{
 SetDCPWM1(0);          // turn off the motor
 uk_1=0;           //in order to start new control loop again from the beginning
 ek_1=0;
break;            //get out of loop
 }
}
} // for the first if condition
```

```
******************/case 3 sensor 3 is > than sensor 4*******************************
 if((Stwo-Sone)>0.3)   // check if difference between them is larger than 0.5 V
{
 ek= Stwo-Sone;            // error signal
 uk=uk_1+(kp+(ki*T/2))*ek+(-kp+(ki*T/2))*ek_1;   //PID of the error signal contain only
P&I elements
 X=400/uk;
 while(1)
 {
 ek= Stwo-Sone;            // error signal
 uk=uk_1+(kp+(ki*T/2))*ek+(-kp+(ki*T/2))*ek_1;   //PID of the error signal contain only
P&I elements
 uk_1=uk;            //previous error signal
 ek_1=ek;
 PORTE=0x02;          // enable motor 1
 SetDCPWM1(0);          // turn off the other direction
```

```
        SetDCPWM2(X*uk);                     //change duty cycle based on changes in output

        if((Stwo-Sone)<0.05)  // if the voltage difference is less than 0.05 V
       {
         SetDCPWM2(0);          // turn off the motor
         uk_1=0;             //in order to start new control loop again from the beginning
         ek_1=0;
        break;            //get out of loop
         }
        }
        } // for the first if condition
}
****************************************************************************//
}
}
****************************//INTERRUPT SUPROUTINE************************
#pragma interrupt analog_inputs
void analog_inputs(void)
{

 ***********************//taking the values of the 1st and 2nd sensors
if(PIR2bits.TMR3IF==1)
{
       SetChanADC(ADC_CH0);             // Channel 0
       ConvertADC();
       while (BusyADC() == 1);
       SLeft = ReadADC();
       SLeft=SLeft*0.00488;   //convert to voltage
```

```
    while (BusyADC() == 1);
    Sright = ReadADC();
    Sright=Sright*0.00488;
    Sright=Sright+0.2;

    SetChanADC(ADC_CH2);          // Channel 0
    ConvertADC();
    while (BusyADC() == 1);
    Sone = ReadADC();
    Sone=Sone*0.00488;   //convert to voltage

    SetChanADC(ADC_CH3);          // Channel 1
    ConvertADC();
    while (BusyADC() == 1);
    Stwo = ReadADC();
    Stwo=Stwo*0.00488;
    Stwo=Stwo+0.2;
    PIR2bits.TMR3IF=0;
    WriteTimer3(45535);
}
}
#pragma code high_vector=0x08
void high_vector(void)
}
_asm goto analog_inputs _endasm
{
#pragma code
```