DESIGN AND IMPLEMENTATION OF A MICROCONTROLLER BASED SOLAR ELEVATION TRACKER

BY

OJI, MADUKA LYNDA

(2000/11143EE)

A PROJECT SUBMITTED

TO

ELECTRICAL AND COMPUTER ENGINEERING DEPARTMENT

SCHOOL OF ENGINEERING & ENGINEERING TECHNOLOGY

FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA.

NOVEMBER, 2005

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SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF BACHELOR OF ENGINEERING (HONOURS) IN ELECTRICAL AND COMPUTER ENGINEERING

NOVEMBER, 2005

DECLARATION

I, OJI - Maduka Lynda (2000/11143EE) hereby declare that this project was carried out by me in the department of Electrical / Computer Engineering under the supervision of Mr. S. N. Rumala.

All information utilized and their sources have been duly acknowledged.

....	07-02-2005 ....
OJI-MADUKA LYNDA	DATE

CERTIFICATION

This is to certify that the project titled "Design and Implementation of a Microcontroller Based Solar Elevation Tracker" was carried out by OJI, Maduka Lynda and submitted to the Electrical and Computer Engineering department, Federal University of Technology Minna, for the award of Bachelor of Engineering degree in Electrical and Computer Engineering.

....7/12/05..........

MR. S. N. RUMALA DATE
(SUPERVISOR)

.... 08/02/2006

ENGR. M. D. ABDULLAHI DATE
(HEAD OF DEPARTMENT)

....

ENGR. DR. J. D. JIYA DATE
(EXTERNAL EXAMINER)

AKNOWLEDGEMENTS

Merriam-Webster describes a journey as something suggesting travel or passage from one place to another. Five years ago a journey began, and now ends with the completion of this project.

Many people helped me reach the end of my passage successfully. First, and foremost, I want to thank God, for He made a way when all roads seemed blocked.

I want to thank my Parents for inspiring me to aim higher, work harder, and reach for the stars.

Many thanks are due to my Sisters; Chioma, Juliet, Christy and their husbands for their words of encouragement, inspiration, and financial assistance. Jane, Joan, Doris and Betsy, what didn't you girls do?

I want to thank The Association of Professional Women Engineers (APWEN) for encouraging me and for whetting my appetite for engineering.

My immediate and extended families deserve many thanks, for they helped me to keep my eyes on the prize.

I want thank all my friends Especially Chidi Ike (C-person), Ogunsola Sunday (Ak-48), Rachael Yisa (Rechy) and all others who helped me reach the end of my journey. Each made my passage unique, and provided perspectives not found in any book or article.

I want to give special thanks to those that helped me with my research and played devils advocate during the entire process. More importantly, I want to thank Mustapha Umar & Akinniyi O Rotimi my partners in this project.

I also want to thank the 'Termites' in room L1, whom I exchanged ideas, laughs, and circumstances with during my passage.

Many people, they know who they are, helped me to develop as a person and Truly realize that obstacles only appear when one takes their eyes off the goal.

A million thanks to my advisor, Mr. Rumala whose wealth of knowledge proved invaluable throughout the whole process as I endured many bumps in the road.

Thank you all for everything.

For all my achievements, Praise be to God, only the mistakes are mine.

DEDICATION

To my beautiful, intelligent, and wonderful mum, Joan. You have given us the strength and focus to accomplish these goals.

ABSTRACT

The potential for solar energy is enormous, since each day the Earth receives in the form of solar energy about 200,000 times the total world electrical-generating capacity. Unfortunately, though solar energy itself is free, the high cost of its collection, conversion, and storage has limited its exploitation.

The main impediment to the widespread use of photovoltaic power is the low conversion efficiency and the high cost of solar cells. However, research efforts have been directed towards the use of concentrators and trackers to produce energy in larger quantities.

A solar tracking system has been designed to operate on one tracking axis. Microcontroller-Based and Closed Loop Control System that combines both electronic and mechanical designs is used to enable the solar cell to seek optimum position for radiant energy.

A mechanism for automatic reset and start has been incorporated in the design. The system satisfactorily tracks the sun from east to west and resets at sunset, with higher efficiency of conversion compared to fixed collectors.

CONTENTS

NOMENCLATURE

Acronyms	Description
BJT	Bipolar Junction Transistor
MOSFET	Metal-Oxide-Semiconductor Field Effect Transistor
PWM	Pulse Width Modulate
SET	Solar Elevation Tracker
MCU	Microcontroller unit
ADC	Analog to digital converter
RISC	Reduced Instruction Set Controller
CMOS	Complementary Metal Oxide Semiconductor
ALU	Arithmetic Logic Unit
CISC	Complex Instruction Set controller
SEA	Solar Elevation Angle

Chapter One

Introduction

1.1 Background

The sun is inevitably and undoubtedly the most abundant and prospective renewable energy source. The Sun radiates solar energy capable of producing heat, causing chemical reactions, or generating electricity.

It is an extremely powerful energy source, and solar radiation is by far the largest source of energy received by the Earth, but its intensity at the Earth's surface is actually quite low.

This is partly because the Earth's atmosphere and its clouds absorb or scatter as much as 54 percent of all incoming sunlight. Despite this, in the 20th century solar energy became increasingly attractive as an energy source owing to its inexhaustible supply and its nonpolluting character, which are in stark contrast to such fossil-fuel sources as coal, oil, and natural gas.

1.2 Solar Radiation and Collection

The sunlight that reaches the ground consists of nearly 50 percent visible light, 45 percent infrared radiation, and smaller amounts of ultraviolet light and other forms of electromagnetic radiation. This radiation can be converted either into thermal energy (heat) or into electrical energy, though the former is easier to accomplish.

Two main types of devices are used to capture solar energy and convert it to thermal energy: flat-plate collectors and concentrating collectors. Because the intensity of solar radiation at the Earth's surface is so low, both types of collectors must be large in area. Even in sunny parts of the world's temperate regions, for instance, a collector must have a surface area of about 430 square feet (40 square m) to gather enough energy to serve one person for one day.

1.3 Generating Electricity from the Sun

Electric power is currently generated from solar energy by two distinct methods. The first, solar thermal electricity requires solar energy to be focused on to a target receiver. The high temperatures created at the target are used either to raise steam, which is used in a conventional thermal power-plant cycle, or are directly harnessed to drive an external combustion engine. The second technology, photovoltaic, uses semi-conductor materials to convert solar radiation directly into electricity.

Solar radiation may be converted directly into electricity by photovoltaic cells. In such cells, a small electrical voltage is generated when light strikes the junction between a metal and a semiconductor (such as silicon) or a junction between two different semiconductors. The voltage generated from a single photovoltaic cell is typically only a fraction of a volt. By connecting large numbers of individual cells together, however, as in modern solar batteries, more than one kilowatt of electric power can be generated. The energy efficiency of most present-day photovoltaic cells is only about 7 to 11 percent; i.e., only that fraction of the radiant energy received is converted to electrical energy. And since the intensity of solar radiation is low to begin with, huge and costly assemblies of such cells are required to produce even moderate amounts of power. Consequently, photovoltaic cells that operate on solar light have so far been used mainly for low-power applications as power sources for calculators and watches, for example. Larger units have been used to provide power for weather and communications satellites. [1]

1.4 Solar Tracking

Observing the sun's motion from any fixed position on the earth's surface over a sufficiently long period of time, the sun would be seen to exhibit regular pattern of daily movement across the sky. Of course, these patterns do vary (longitudinally), gradually throughout the year. The position of the sun at any chosen time can be fully designed using two angles that are measured from a fixed location. One of these angles is called solar altitude and the other solar azimuth, and both depend upon time of the year, time of the day and latitude of the point of reference. While in itself, the time of the day can be calculated from the hour angle.

The strength of the solar energy available at any point on the Earth depends, in a complicated but predictable way, on the day of the year, the time of day, and the latitude of the collection point. Furthermore, the amount of solar energy that can be collected depends on the orientation of the collecting object. [2]

Since the various movements of the earth make the radiation pattern to vary with time of the day, year and so on, it becomes impossible to collect maximum radiation throughout the sun day with a fixed collector. It becomes obvious that consistent alignment of the collector must be ensured to always obtain maximum radiation from the sun. In the application of photovoltaic cells most especially, solar tracking enhances efficiency most especially for concentrators.

Automation of the solar collectors could be obtained where the unit can operate without the need of human intervention once set to work. Such system can track the sun so that the solar panel receives maximum radiation during sun hour periods. However, the structure used to support and impart tracking motion to the panels represents a large portion of the overall cost. This may be the reason why such systems have not yet gained the same popularity as fixed collectors.

1.5 Microcontroller based Solar Tracker

The Microcontroller-based Tracker greatly improves the performance of the PV system by letting the PV panels follow the course of the sun, so that the Panel surface is always in an optimum angle to the sun rays to guarantee highest efficiency.

The idea is to design the electronics for a simple device that tracks a light source. This is used to keep a solar panel (or telescope) aligned with the sun. This will be done using two photocells that are separated with an opaque divider. The cells are connected to a microcontroller, and the circuit is designed to read the output of the photocells and turn the motor in the direction of the brightest light. When the two photocells register the same amount of light, it is pointing directly at the light source.

1.6 Scope of work

The solar elevation tracker is essentially a closed loop control system that combines both electronic and mechanical designs. The system components are the microcontroller logic circuitry, suitable DC motor driver (H-Bridge), Photointerrupter used as Incremental Optical Shaft Encoder (Tachometer, Limit Sensor) and Cds photoconductive cells (photosensors). The DC motor driver is controlled by a PWM signal produced by the microcontroller. The microcontroller does so by reading the data at the output of the photosensors and Photointerrupters simultaneously, which can then be sent to control the motor position.

Chapter Two

Literature Review

2.1 Historical Perspective of Solar Energy Application

In order to obtain maximum energy from the sun, various methods have been employed in the time past.

The earliest known record of the direct conversion of solar radiation into mechanical power belongs to Auguste Mouchout, a mathematics instructor at the Lyce de Tours. Mouchout began his solar work in 1860 after expressing grave concerns about his country's dependence on coal. By the following year he was granted the first patent for a motor running on solar power and continued to improve his design until about 1880. During this period the inventor laid the foundation for our modern understanding of converting solar radiation into mechanical steam power.

Mouchout's initial experiments involved a glass-enclosed iron cauldron: incoming solar radiation passed through the glass cover, and the trapped rays transmitted heat to the water. In late 1865, he succeeded in using his apparatus to operate a small, conventional steam engine. By the following summer, Mouchout enlarged his invention's capacity, refined the reflector, redesigning it as a truncated cone, like a dish with slanted sides, to more accurately focus the sun's rays on the boiler. Mouchout also constructed a tracking mechanism that enabled the entire machine to follow the sun's altitude and azimuth, providing uninterrupted solar reception.

William Adams, the deputy registrar for the English Crown in Bombay, India noted that he was intrigued with Mouchout's solar steam engine after reading an account of the

Tours demonstration, but that the invention was impractical. He however offered some creative solutions. For example, Adams was convinced that a reflector of flat silvered mirrors arranged in a semicircle would be cheaper to construct and easier to maintain. Confident of his innovative arrangement, Adams began construction in late 1878.He built a large rack of many small mirrors and adjusted each one to reflect sunlight in a specific direction. To track the sun's movement, the entire rack could be rolled around a semicircular track, projecting the concentrated radiation onto a stationary boiler. The rack could be attended by a laborer and had to be moved only three or four times during the day, or more frequently to improve performance.

Adam's legacy of producing a powerful and versatile way to harness and convert solar heat survives. Engineers today know this design as the Power Tower concept, which is one of the best configurations for large scale, centralized solar plants.

As the years wore on, newer methods were designed for collecting as well as tracking the sun. These included;

Engineer Charles Tellier's method of collection without reflection. By 1889 Tellier had increased the efficiency of the collectors by enclosing the top with glass and insulating the bottom.

Around 1870, U.S. engineer John Ericsson invented a novel method for collecting solar rays--the parabolic trough. A parabolic trough is more akin to an oil drum cut in half lengthwise that focuses solar rays in a line across the open side of the reflector. This type of reflector offered many advantages over its circular counterparts: it was comparatively simple, less expensive to construct, and, unlike a circular reflector, had only to **track** the sun in a single direction thus eliminating the need for complex tracking machinery. The downside was that the device's temperatures and efficiencies were not as high as with a dish-shaped reflector,

The First Commercial Venture was by Aubrey Eneas who began his solar motor experimentation in 1892, and formed the first solar power company (The Solar Motor Co.) in 1900. Though the machine did not become a fixture as Eneas had hoped, the inventor contributed a great deal of scientific and technical data about solar heat conversion and initiated more than his share of public exposure. [3]

2.2 A Technical Maturity

The past 25 years have witnessed the emergence of various methods of solar energy collection as a result of the improvement in technology witnessed within this period. Some of our brightest engineers have even produced some exemplary solar power designs during the period.

A shadow method for automatic tracking, which is an automatic method that uses 'back-to-back' semi-cylinders to mask solar irradiation was described and later presented for publication at the Solar World Congress 1987 in Hamburg by Sode-Shinni Nmadu Rumala. [4]. A (time-based) solar tracking system was also designed based on single axis tracking, on the equatorial tracking axis to track the sun from east to west daily during sun hour periods. An open loop control mode was adopted using logic control circuit and suitable interface for the stepper motor and other circuitry. A start and reset circuit was also incorporated to further enhance the automation of the tracker. (Final year project Bauchi)

The aforementioned solar pioneers were only few of the most notable inventors involved in the development of solar thermal power from 1860 to date. Many others contributed to the more than 50 patents and the scores of books and articles on the subject. Solar technology already boasts a century of R&D, requires no toxic fuel and relatively little maintenance, is inexhaustible, and, with adequate financial support, is capable of becoming directly competitive with conventional technologies in many locations. These attributes make solar energy one of the most promising sources for many current and future energy needs. As Frank Shuman declared more than 80 years ago, it is "the most rational source of power."

Chapter Three

Design and Implementation

3.1 Overview

The solar elevation tracker is essentially a closed loop control system that covers both the fields of electronics and mechanical engineering. The components of the electronic system consist of a Microcontroller logic circuitry, Phototransistor optocouplers as Isolators, DC motor driver (H-Bridge), Photointerrupter used as Incremental Optical Shaft Encoder (Tachometer, Limit Sensor) and Cadmium Sulphide photoconductive cells (photosensors). The DC motor driver is controlled by a PWM signal produced by the microcontroller. The microcontroller, using data acquisition and processing is able to determine the position, and limit range of the solar panels. It does so by reading the data at the output of the photosensors and Photointerrupters simultaneously, which can then be sent to control the motor position. Figure 3-1 shows a block diagram of the system.

3.2 Electrical System Description

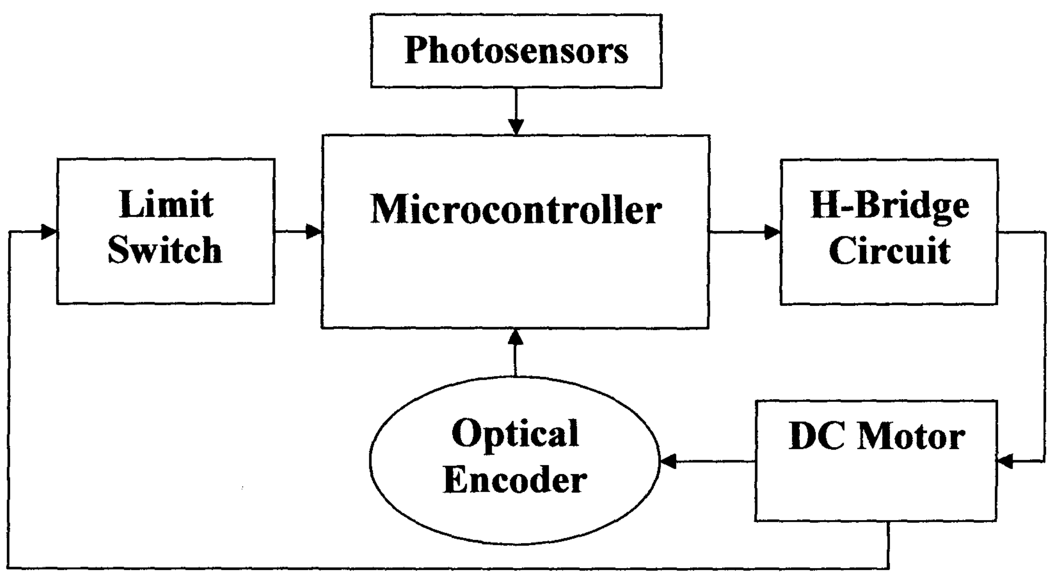


Figure 3-1: Block diagram of the system

3.2.1 Photosensor

Cadmium Sulphide (Cds) photoconductive cells are used as photosensors. It is a type of light dependent resistor (LDR) semiconductor that operates much like a thermistor. In an intrinsic semiconductor, photons (Blue arrow) can promote an electron (Black arrow) to the conduction band leaving a hole in the valence band. This increase in carriers leads to a reduction in the resistance. That is as light hits the Cds it knocks charge carriers loose, and the increased number of carriers decreases the resistance of the device. Cadmium sulphide photoconductive cell has energy gap of 2.42 electron volts (eV) and a wavelength of wavelength 5130 (Å). Figure 3-2 shows the Schematic symbol and energy band of Cadmium sulphide photoconductive cell.

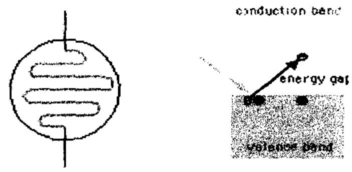


Figure 3-2: Schematic symbol and Energy band of Cds cell

3.2.2 Phototransistor Optocoupler

Phototransistor Optocoupler can be used to provide isolation between components, to avoid ground loop problems, to control floating electronics, and to provide DC shifts. Also applicable to Power supply regulators, Digital logic inputs and Microprocessor inputs. Figure 3-3 shows its schematic symbol and 6-pin dual in-line package.

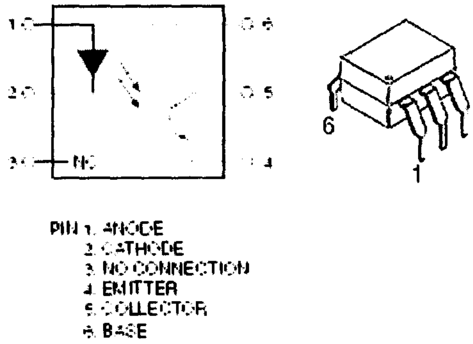


Figure 3-3: Optocoupler schematic symbol and 6pin dual in-line package

The general purpose optocouplers consist of a gallium arsenide infrared (IR) emitting diode spectrally matched to drive a silicon phototransistor.

The IR diode section gives up excess energy in the form of photon when electrons and holes combine in the depletion region. This energy is a characteristic of the materials from which the junction is constructed and thus the photon always has the same wavelength. To emit Photons, the junction must be forward biased and the wavelength must also be in the infrared spectrum.

The phototransistor section of the optocoupler is an NPN bipolar transistor with a large base that does not have a lead. When photons (from IR emitting diode) hit the base they create electron/hole pairs, the electrons are drawn to the collector and the holes are filled with electrons from the emitter. Thus there is a current from the collector to emitter.

3.2.3 H-Bridge

A microprocessor or microcontroller cannot drive a motor directly, since it cannot supply enough current. Instead, there must be some interface circuitry so that the motor power is supplied from another power source and only the control signals are derived from the microprocessor. This interface circuitry can be implemented by a circuit known as the H-bridge. It is the primary means for driving a motor in the forward and reverse directions. It merely consists of 4 switches A, B, C, D connected in topology of an H, where the motor terminals form the crossbar of the H. figure 3-4 shows an H-bridge circuit.

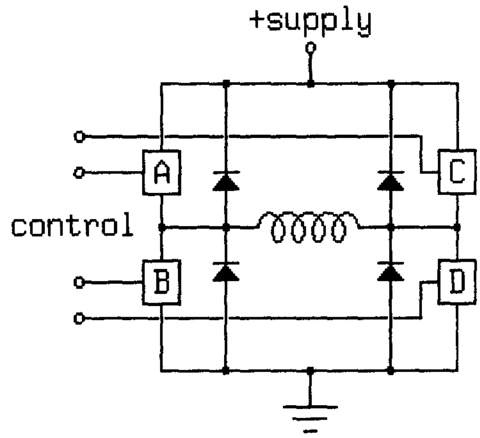
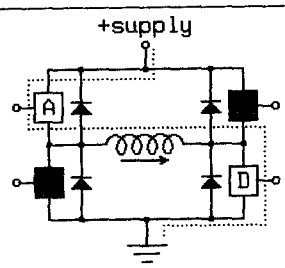
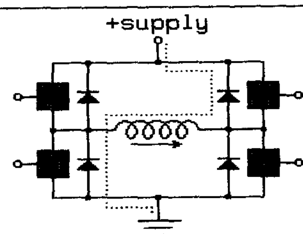
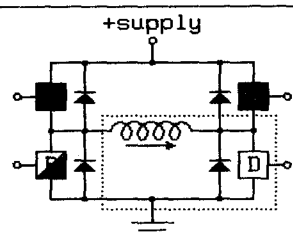


Figure 3-4 H-Bridge circuit

It is worth noting that H-bridges are not only applicable to the control of motors, but also to the control of push-pull solenoids (those with permanent magnet plungers) and many other applications. With 4 switches, the basic H-bridge offers 16 possible operating modes, 7 of which short out the power supply. The desired operating modes are illustrated in table-3.1 below.

Table 3-1- H-Bridge operating modes (Close = 1, Open = 0)

Mode	A	B	C	D	Figure	Comment
1	1 0	0 1	0 1	1 0		(1)Forward (2)Reverse
2	0	0	0	0		Fast decay (coasting)
3	0	X	0	1		Slow decay or dynamic braking

MODE 1: Forward and Reverse are the usual operating modes, allowing current to flow from the supply, through the motor winding and onward to ground.

MODE 2: In Fast decay or coasting mode, any current flowing through the motor winding will be working against the full supply voltage, plus two diode drops, so current will decay quickly. This mode provides little or no dynamic braking effect on the motor rotor, so the rotor will coast freely if all motor windings are powered in this mode.

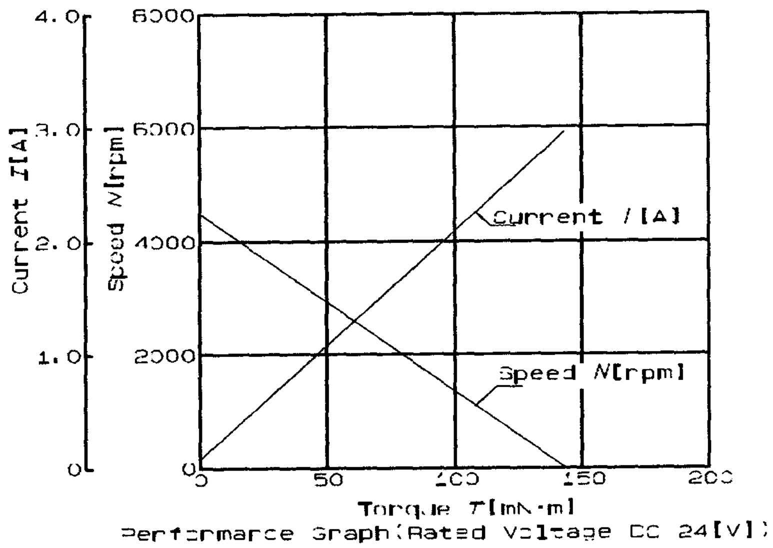
MODE 3: In Slow decay or dynamic braking modes, current may re-circulate through the motor winding with minimum resistance. As a result, if current is flowing in a motor winding when one of these modes is entered, the current will decay slowly, and if the motor rotor is turning, it will induce a current that will act as a brake on the rotor.

3.2.4 DC Motor

The direct current (DC) motor is one of the first machines devised to convert electrical energy to mechanical power. Its origin can be traced to machines conceived and tested by Michael Faraday, the experimenter who formulated the fundamental concepts of electromagnetism. Most of the world's adjustable speed business is addressed by DC motors. DC motors are utilized in applications where speed control, servo control, and/or positioning needs exist. Several characteristics are important in selecting a DC motor. Listed below, the first two are DC Motor's input ratings that specify its electrical characteristics and the last three are ratings describing the motor's output characteristics:

- Operating Voltage (V)
- Operating Current (I)
- Speed (RPM)
- Torque (Nm)
- Power (V)

The power delivered by a motor is the product of its speed and the torque at which the speed is applied. Graph 3-1 shows relationship between these characteristics.



Graph 3-1- DC Motor Characteristics

3.2.5 Optical Encoder

Optical encoder is a type of feedback device that gives information on the system's stabilization, speed and position. It is simply used as a digital tachometer for absolute and incremental position encoding. When the motor's shaft is rotated the encoder gives an output signal proportional to distance (i.e. angle) the shaft is rotated through. It provides a specific address for each shaft position throughout 360 degrees coded onto a disk. The number of tracks on the coded disk may be increased until the desired resolution or accuracy is achieved. A light source passes a beam through the transparent segments onto the encoder's photosensor which outputs a sinusoidal waveform or pulse train. If the output signal is just a sinusoidal waveform, electronic processing can be used to transform the signal into a square pulse train. This is illustrated in figure 3-5.

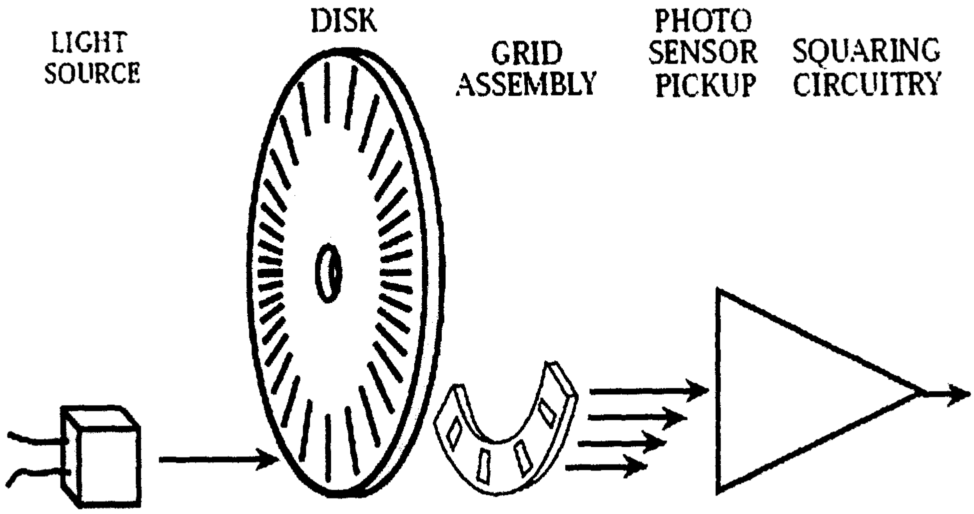


Figure 3-5: Incremental Encoder

In utilizing this device, the following parameters are important:

- **Line count-** This is the number of pulses per revolution. The number of lines is determined by the positional accuracy required in the application.
- **Output signal-** The output from the photosensor can be either a Sine or square wave signal.
- **Number of channels-** Either one or two channel outputs can be provided. The two channel version provides a signal relationship to obtain motion direction (i.e. clockwise or counterclockwise rotation).

In addition, a zero index pulse can be provided to assist in determining the "home" position.

A typical application using an incremental encoder is as follows: An input signal loads a counter with positioning information. This represents the position the load must be moved to. As the motor accelerates, the pulses emitted from the incremental (digital) encoder come at an increasing rate until a constant run speed is attained. During the run period, the pulses come at a constant rate which can be directly related to motor speed. The counter, in the meanwhile, is counting the encoder pulses and, at a predetermined location, the motor is commanded to slow down. This is to prevent overshooting the desired position. When the counter is within 1 or 2 pulses of the desired position, the motor is commanded to stop with the load is now in position. [5, 6, 7, 8]

3.2.6 Limit Switch

The limit switch provides the system with a maximum and minimum allowable travel range. Zero index pulse signal from the Optical encoder determines either of the limits which after a certain delay, the "home" position will be reset.

3.2.7 Microcontroller

A microcontroller (often abbreviated MCU) is a single computer chip (integrated circuit) that executes a user program, normally for the purpose of controlling some device. It is ideal for the types of applications where cost and unit size are very important considerations. Nowadays it is almost always desirable to produce circuits that require the smallest number of integrated circuits, that require the smallest amount of physical space, require the least amount of energy, and cost as little as possible.

The type used in this project is an ATmega16 which is a low-power CMOS 8-bit microcontroller based on the AVR enhanced RISC architecture. By executing powerful instructions in a single clock cycle, the ATmega16 achieves throughputs approaching 1 MIPS per MHz allowing the system designer to optimize power consumption versus processing speed. This particular Atmel MCU family was chosen because its AVR core combines a rich instruction set with 32 general purpose working registers. All the 32 registers are directly connected to the Arithmetic Logic Unit (ALU), allowing two independent registers to be accessed in one single instruction executed in one clock cycle.

The resulting architecture is more code efficient while achieving throughputs up to ten times faster than conventional CISC microcontrollers such as the 8051/8052.

The ATmega16 provides the following features: 16K bytes of In-System Programmable Flash Program memory with Read-While-Write capabilities, 512 bytes EEPROM, 1K byte SRAM, 32 general purpose I/O lines, 32 general purpose working registers, a JTAG interface for Boundary-scan, On-chip Debugging support and programming, three flexible Timer/Counters with compare modes, Internal and External Interrupts, a serial programmable USART, a byte oriented Two-wire Serial Interface, an 8-channel, 10-bit ADC with optional differential input stage with programmable gain, a programmable Watchdog Timer with Internal Oscillator, an SPI serial port, and six software selectable power saving modes. Figure 3-6 shows the detailed block diagram of such MCU.

The ATmega16 AVR is supported with a full suite of program and system development tools including: C compilers, macro assemblers, program debugger/simulators, in-circuit emulators, and evaluation kits. [9]

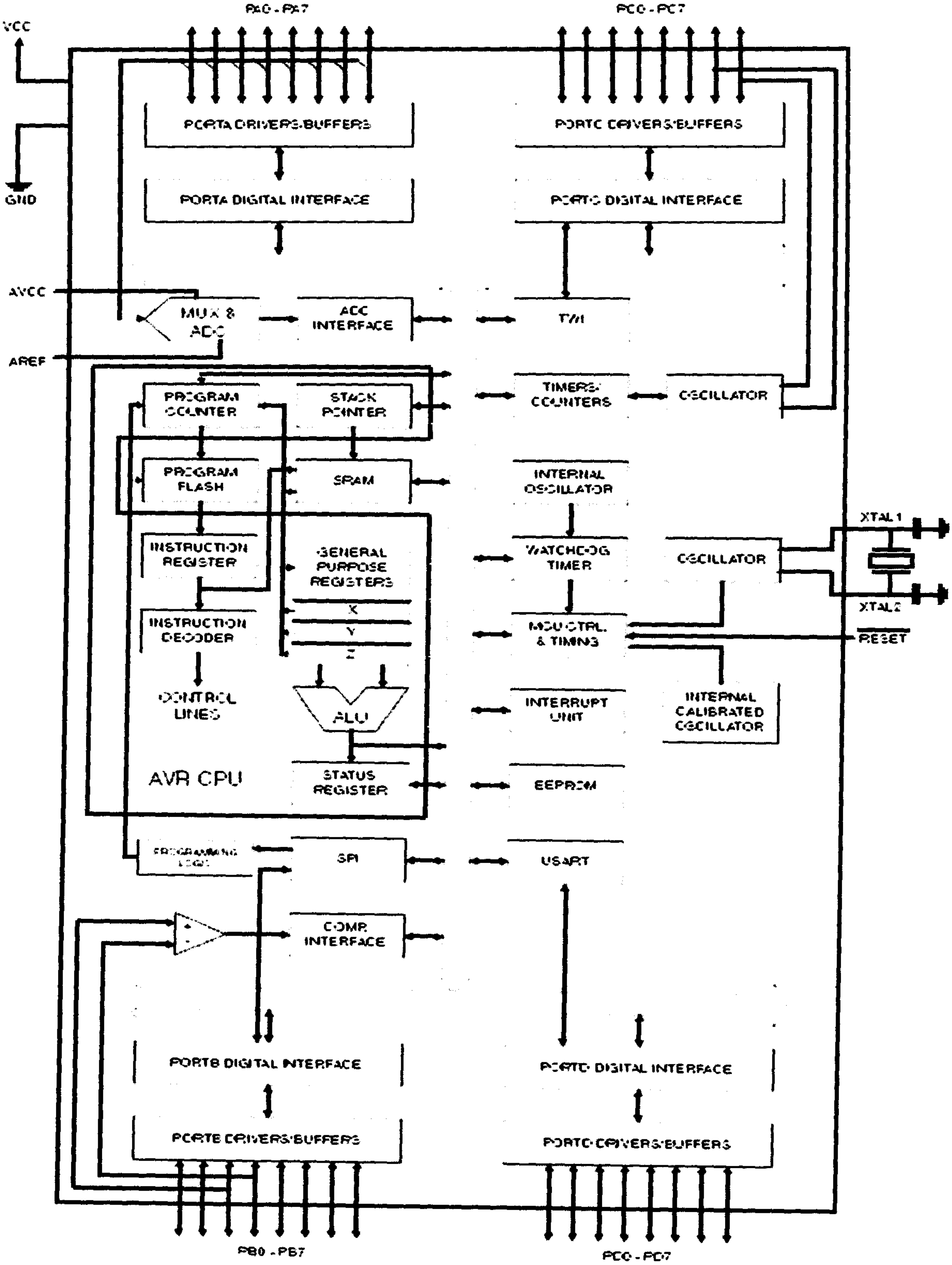


Figure 3-6: ATmega16 Block Diagram

3.3 Electrical System Design

3.3.1 Optocoupled Motor Control Circuit

The Optocoupled motor control circuit is not very complex, it is an integral part of the sun tracking machine. It must be able to interface to the MCU, turn the motor on and off, allow the current through the motor to be reversed, and control the speed of the motor for tracking adjustments. The circuit being used in a power tracking system, must also be able to track with minimum power usage. However, DC motors require a relatively high voltage for the initial start. Lower voltages don't give the motors enough torque, which made it unreliable and very sluggish. In order to solve this problem and conserve power, PWM control signal generated from the MCU was used to pulse the power to the Optocoupled motor control circuit. By adjusting the duty cycle of the PWM signal, various voltage levels can be generated. When the duty cycle is set at 100%, the motor receives all of the voltage being supplied to it, but when the duty cycle is 50%, the effective voltage at the motor is half of the voltage being supplied to it. Thus, the speed of the motors can be varied, while the torque remains constant with minimum power usage. [10]

The inputs for the Optocoupled motor control circuit attach directly to the outputs of the microcontroller. The Optocoupled motor control circuit is shown in figure 3-7

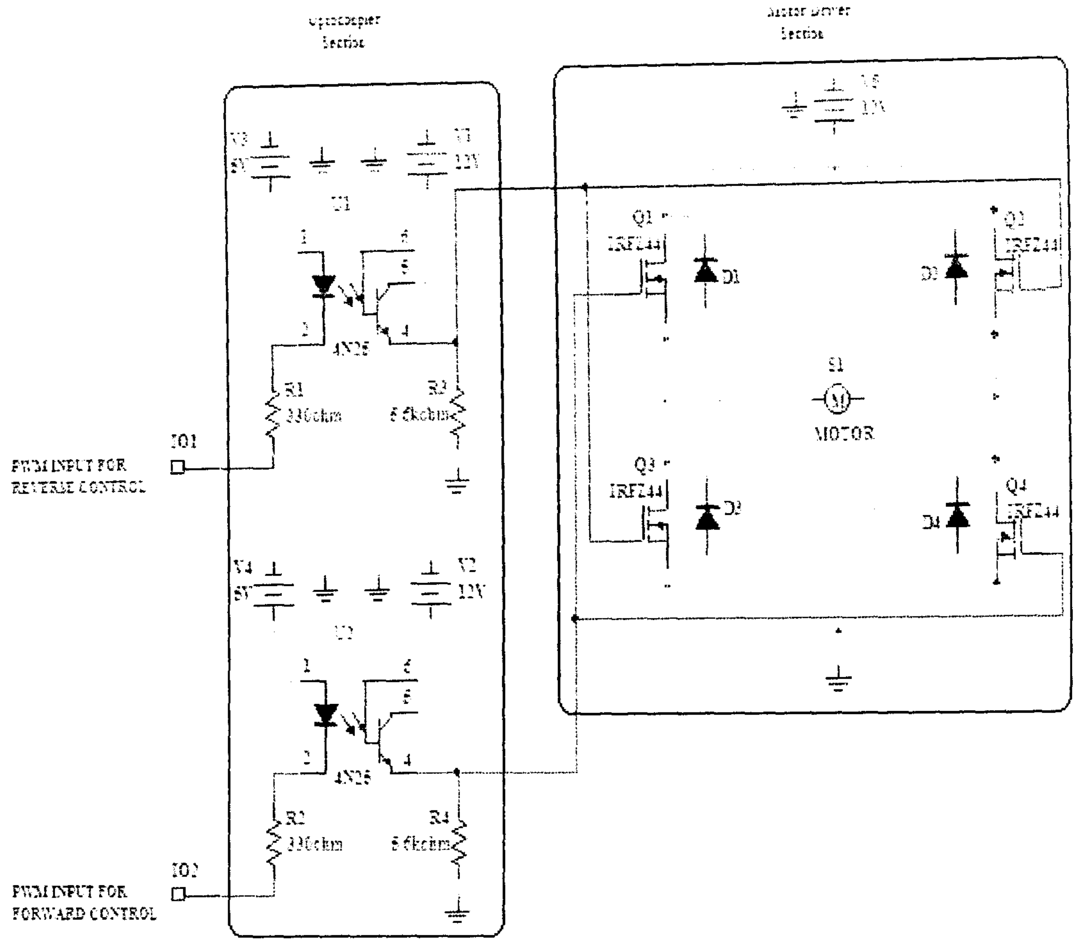


Figure 3-7: Optocoupled Motor Control Circuit

ISOLATION

To completely isolate the motor driver circuit, which consist of the H-Bridge, from the MCU, two 4N25 phototransistor Optocouplers were used to detach the two MCU lines from their H-Bridge counterparts. This device uses an infrared diode to turn a phototransistor on and off. When the MCU passes a low level signal, current passes through the photodiode and the phototransistor is essentially a closed switch; its output voltage level will be raised from ground to 12V. When the MCU passes a high level signal, the photodiode is off and the phototransistor is an open circuit; with its output pulled-down to ground through the 5.6kOhm resistor. The optocouplers are in an inverting configuration, therefore, rather than inputting a signal referenced to 5v, ground was used as the input and was referenced to each of the two signals.

Once the signals are inverted through the optocoupler's phototransistor, the correct signals are passed to the H-bridge, with exception that a logical high is 12V rather than 5V. Since the optocouplers use phototransistors that receive IR signals, there is no physical connection between the MCU's circuit and the H-bridge. Hence, no noise from the motor can go to the MCU.

DRIVER OPERATION

Applying a potential to the motor leads will cause the motor to spin in one direction, while reversing the polarity on the leads will cause the DC motor to pin in the opposite direction. To control the motor's forward and reverse motion, a simple 4-switch device is required (See Table 3.1) that would ensure protection against a short of the DC supply, that is, switches 1 and 2 or 4 and 3 could never be closed at the same time. To operate the motor in one direction, simply close switches 1 and 4; for reverse operation, open switches 1 and 4 and close switches 2 and 3. To stop the motor completely, simply open all switches. To properly control the motor with high speed switching, a circuit configuration called an H-bridge (See Figure 3.6) was implemented.

MOSFET transistors were implemented as switches in place of BJTs for one main reason - to improve the efficiency of the bridge. This is because the BJT transistors (normal transistors), though more linear with better gain have a saturation voltage of approximately 1V across the collector emitter junction when turned on. An H-bridge having power supply of 12V would be consuming 2V (16.6%) across the two transistors required to control just the direction of the current. It is therefore inefficient for an energy collection project to waste 16.7% of its supply just to control current direction. The BJTs also would get quite hot and there is no room for heat sinks. However, IRF44 MOSFETs were used simply because of their low ON resistance ($R_{DS\ (ON)}$ =0.023Ω). This is the resistance between the Drain and Source when turned on. At 4 amps, this makes the voltage drop per MOSFET to be 0.092V and 0.184V (1.5% of the power supply) for the two required to control the direction of the current. This is a definite improvement on the driver's efficiency.

Four protection diodes were used; one per MOSFET to ensure there is never a short from the supply to ground. D1 to D4 route back EMF from the motor back to the power supply. Some MOSFETs (actually most) have these diodes built-in, so they may not be necessary.

MOSFETs work by applying a voltage to the Gate. They call this TRANSCONDUCTANCE, which is the rate of change of the drain current with a change of the gate bias. When a positive voltage greater than the Gate threshold voltage is applied, the MOSFET turns on (N Channel only. The P channel works in reverse). One of the most important uses of MOSFETs is to build logic circuits that dissipate very little power.

3.3.2 ATmega16 MCU

HARDWARE

The electronic system was implemented around an ATmega16 MCU running on 4 MHz Internal RC Oscillator for tracking algorithm to find the Solar Elevation Angle (SEA). The MCU monitors the operating state of the system to ensure proper operation and sequence of events. Its timers, ADC and I/O ports features were used in this project. 8-bit timer/counter0 and 16-bit timer/counter1 controls the motor permissible ON duration, and fast PWM wave generation respectively. The ADC digitizes the voltage from a photosensor on the panel, and uses this information to control the driving voltage of a DC motor.

TIMER/COUNTER 0

The simplified block diagram of the 8-bit Timer/Counter0 is shown in Figure 3-7.

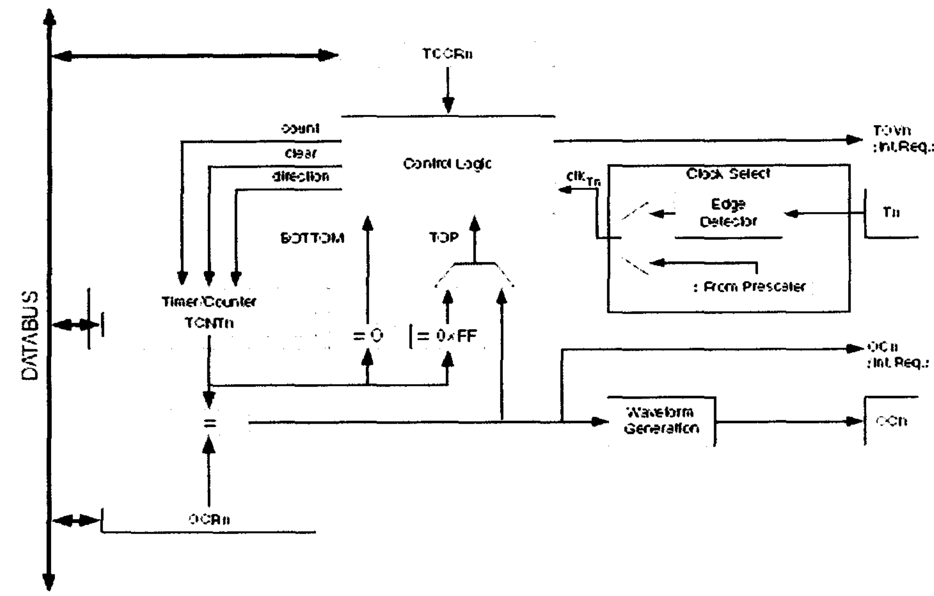


Figure 3-8: 8-bit Timer/Counter

The timer0 is configured to operate in its overflow mode. The overflow event causes the Timer Overflow Flag (TOV0) to be set in the Timer

Interrupt Flag Register (TIFR). Whenever this timer0 overflow occurs the motor timer will be decremented by 1. The motor ON duration was chosen to be 0.05 seconds. This timing was achieved by proper prescaling of the 4 MHz internal RC resonator to 3.906 KHz (4MHz/1024). The prescaled frequency value indicates that a timer0 overflow flag is triggered every 256μsec (1/3.906 KHz). However, to get a 0.05 second 195 overflows must elapse; therefore the motor timer was loaded with value 195. Figure 3-9 shows the prescaler block diagram of timer 0&1 together with the table 3.2 for prescaler clock select bit description.

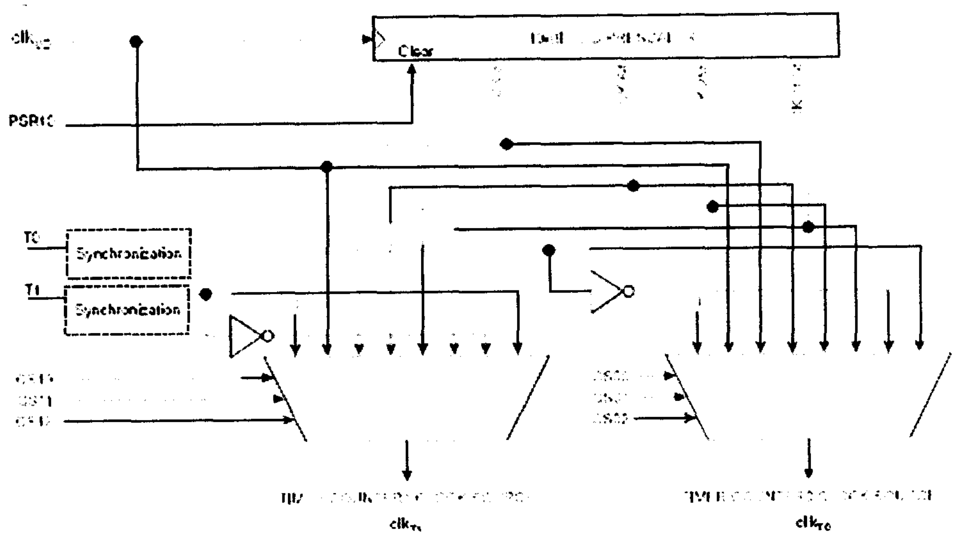


Figure 3-9: Prescaler block diagram of timer 0&1

Table 3-2- clock select bit description

CS02	CS01	CS00	Description
0	0	0	No clock source (Timer/Counter stopped).
0	0	1	$clk_{I/O}$/(No prescaling)
0	1	0	$clk_{I/O}$/8 (From prescaler)
0	1	1	$clk_{I/O}$/32 (From prescaler)
1	0	0	$clk_{I/O}$/256 (From prescaler)
1	0	1	$clk_{I/O}$/1024 (From prescaler)
1	1	0	External clock source on T0 pin. Clock on falling edge.
1	1	1	External clock source on T0 pin. Clock on rising edge.

From the table above, the timer was prescaled to the required frequency by dividing the Internal clock (F_{CPU}) by a prescaler value 1024. This was achieved by setting both the CS02, CS00 (clock select bit of the timer0 control register) and clearing CS01. Refer to appendix 'B' for memory map showing the register summary.

TIMER/CONTER 1

The simplified block diagram of the 16-bit Timer/Counter1 is shown in Figure 3-10.

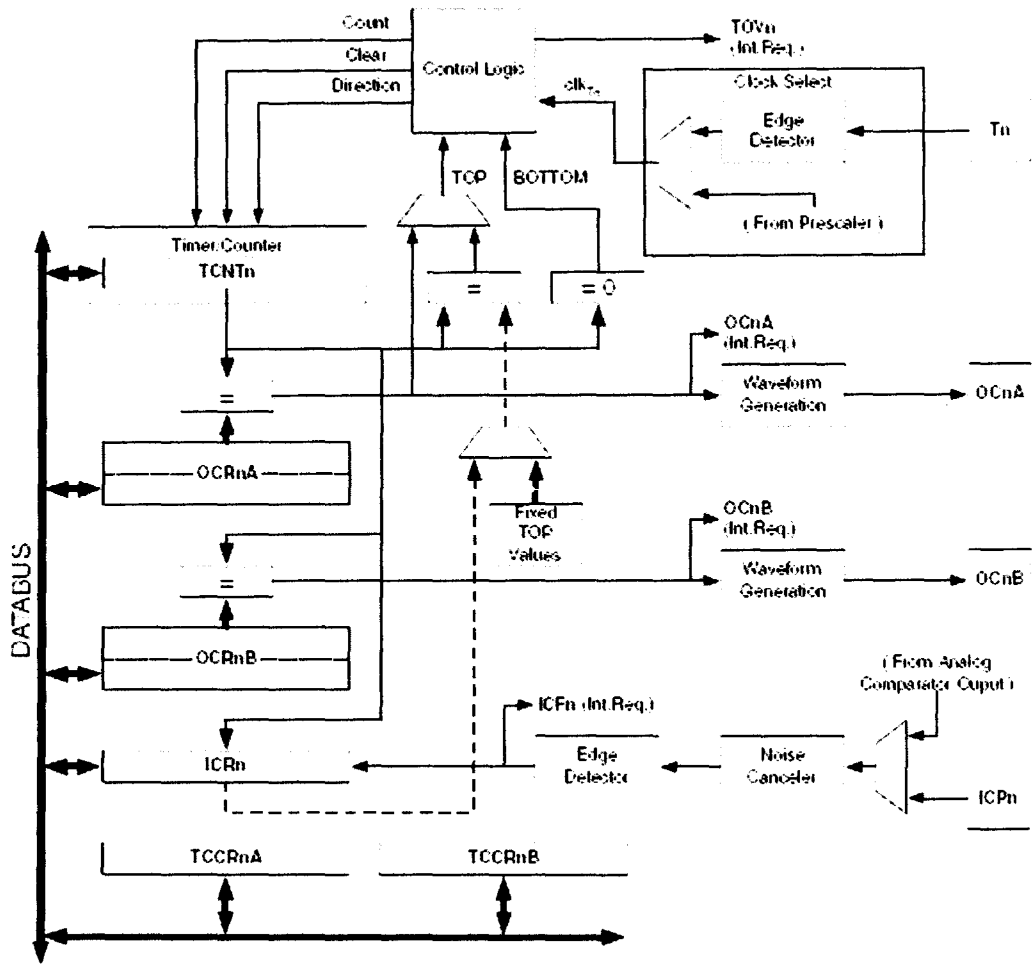


Figure 3-10: 16-bit Timer/Counter

The 16-bit Timer/Counter unit allows accurate program execution timing (event management), wave generation, and signal timing measurement. The wave generation mode 14 (see table 3.3) was used to generate the fast PWM signal required for either forward or reverse motion.

Table 3-3- Waveform Generation Mode Bit Description

Mode	WGM13	WGM12 (CTC1)	WGM11 (PWM11)	WGM10 (PWM10)	Timer/Counter Mode of Operation	TOP	Update of OCR1X	TOV1 Flag Set on
0	0	0	0	0	Normal	0xFFFF	Immediate	MAX
1	0	0	0	1	PWM, Phase Correct, 8-bit	0x00FF	TOP	BOTTOM
2	0	0	1	0	PWM, Phase Correct, 9-bit	0x01FF	TOP	BOTTOM
3	0	0	1	1	PWM, Phase Correct, 10-bit	0x03FF	TOP	BOTTOM
4	0	1	0	0	CTC	OCR1A	Immediate	MAX
5	0	1	0	1	Fast PWM, 8-bit	0x00FF	TOP	TOP
6	0	1	1	0	Fast PWM, 9-bit	0x01FF	TOP	TOP
7	0	1	1	1	Fast PWM, 10-bit	0x03FF	TOP	TOP
8	1	0	0	0	PWM, Phase and Frequency Correct	ICR1	BOTTOM	BOTTOM
9	1	0	0	1	PWM, Phase and Frequency Correct	OCR1A	BOTTOM	BOTTOM
10	1	0	1	0	PWM, Phase Correct	ICR1	TOP	BOTTOM
11	1	0	1	1	PWM, Phase Correct	OCR1A	TOP	BOTTOM
12	1	1	0	0	CTC	ICR1	Immediate	MAX
13	1	1	0	1	Reserved	–	–	–
14	1	1	1	0	Fast PWM	ICR1	TOP	TOP
15	1	1	1	1	Fast PWM	OCR1A	TOP	TOP

This was achieved by setting the WGM13 and WGM12 bits of TCCR1A (timer1 control register A), and also setting the WGM11 and clearing WGM10 bits of TCCR1B (timer1 control register B).

The *fast Pulse Width Modulation* or fast PWM mode 14 provides a high frequency PWM waveform generation option required to pulse the DC motor. The counter counts from BOTTOM to TOP then restarts from BOTTOM. The value to be compared with was stored in the 16-bit output compare register (OCR1AH/L and OCR1BH/L), so that whenever a compare match occurs between the counter and the content of OCR1 (either for A or B depending on the selected motor direction), the pin considered (OC1 A or B for pin5 or pin4 respectively) will be cleared to 0. It will also be set back to 1 when the counter eventually reaches it top value. That is in inverting Compare Output mode output is cleared on compare match and set at TOP. The table below illustrates the different types of compare modes utilized by the MCU.

Table 3-4- Compare Output Mode.

COM1A1/COM1B1	COM1A0/COM1B0	Description
0	0	Normal port operation, OC1A/OC1B disconnected.
0	1	WGM13 = 0: Normal port operation. OC1A/OC1B disconnected. WGM13 = 1: Toggle OC1A on compare match, OC1B reserved.
1	0	Clear OC1A/OC1B on compare match, set OC1A/OC1B at TOP
1	1	Set OC1A/OC1B on compare match, clear OC1A/OC1B at TOP

The above mentioned mode was achieved when the Compare Output Mode for Channels A and B pin of TCCR1A were set and cleared respectively. Although the minimum PWM resolution allowed is 2-bit (ICR1 or OCR1A set to 0x0003), and the maximum resolution is 16-bit (ICR1 or OCR1A set to MAX), the resolution for fast PWM was fixed to 8-bit.

The PWM resolution in bits was calculated by the following equation:

$$R_{FPWM} = \log(top+1)/\log 2$$

In fast PWM mode the counter is incremented until the counter value matches either one of the fixed values in OCR1A. The counter is then cleared at the following timer clock cycle. This is shown in the timing diagram of Figure 3.11.

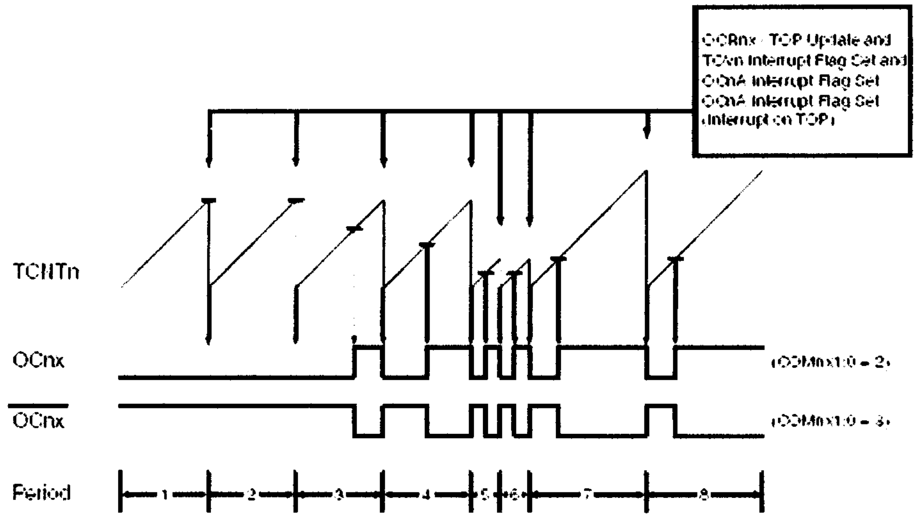


Figure 3-11: Fast PWM timing diagram

The figure shows fast PWM mode when OCR1A was used to define the TOP value. The TCNT1 value is in the timing diagram shown as a histogram for illustrating the single-slope operation. The diagram includes non-inverted and inverted PWM outputs. The small horizontal line marks on the TCNT1 slopes represent compare matches between OCR1A/B and TCNT1. The OC1 A/B interrupt flag will be set when a compare match occurs. The Timer/Counter Overflow Flag (TOV1) is set each time the counter reaches TOP. In addition, the OC1A/B or ICF1 flag is set at the same timer clock cycle as TOV1 is set when either OCR1A/B was used for defining the TOP value. When changing the TOP value it was ensured that the new TOP value was higher or equal to the value of all of the compare registers. However, if the TOP value were to be lower than any of the compare registers, a compare match will never occur between the TCNT1 and the OCR1A/B. The ICR1 Register was used for defining the fixed TOP values. By using ICR1, the OCR1A Register is free to be used for generating a PWM output on OC1A.

The I/O Pin 4 and Pin 5 of the MCU's port were configured to override the generated PWM signal and were connected to the Optocoupled Motor Control Circuit.

Figure 3-12 shows a simplified schematic of the logic affected by the COM1A/B1:0 bit setting achieved.

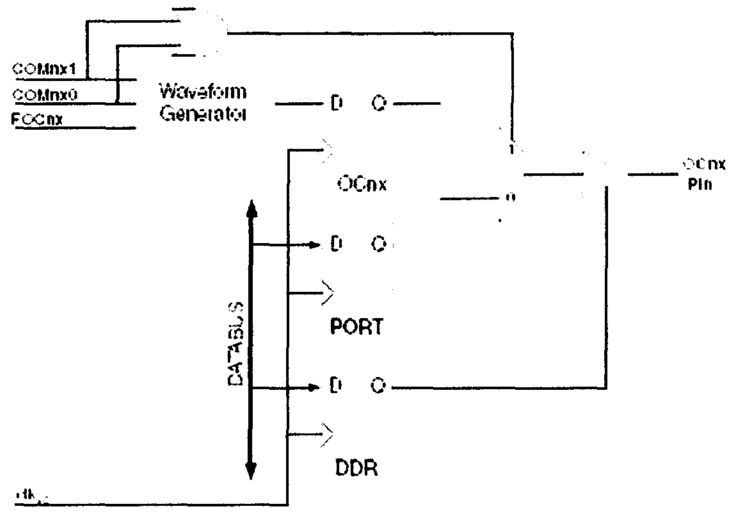


Figure 3-12 Compare Match Output Unit, Schematic (x=either A/B)

ANALOG TO DIGITAL CONVERTER

The ATmega16 features a 10-bit successive approximation ADC. The ADC is connected to an 8-channel Analog Multiplexer which allows 8 single-ended voltage inputs constructed from the pins of Port A. The single-ended voltage inputs refer to 0V (GND). The ADC contains a Sample and Hold circuit which ensures that the input voltage to the ADC is held at a constant level during conversion. A block diagram of the ADC is shown in Figure 3-13.

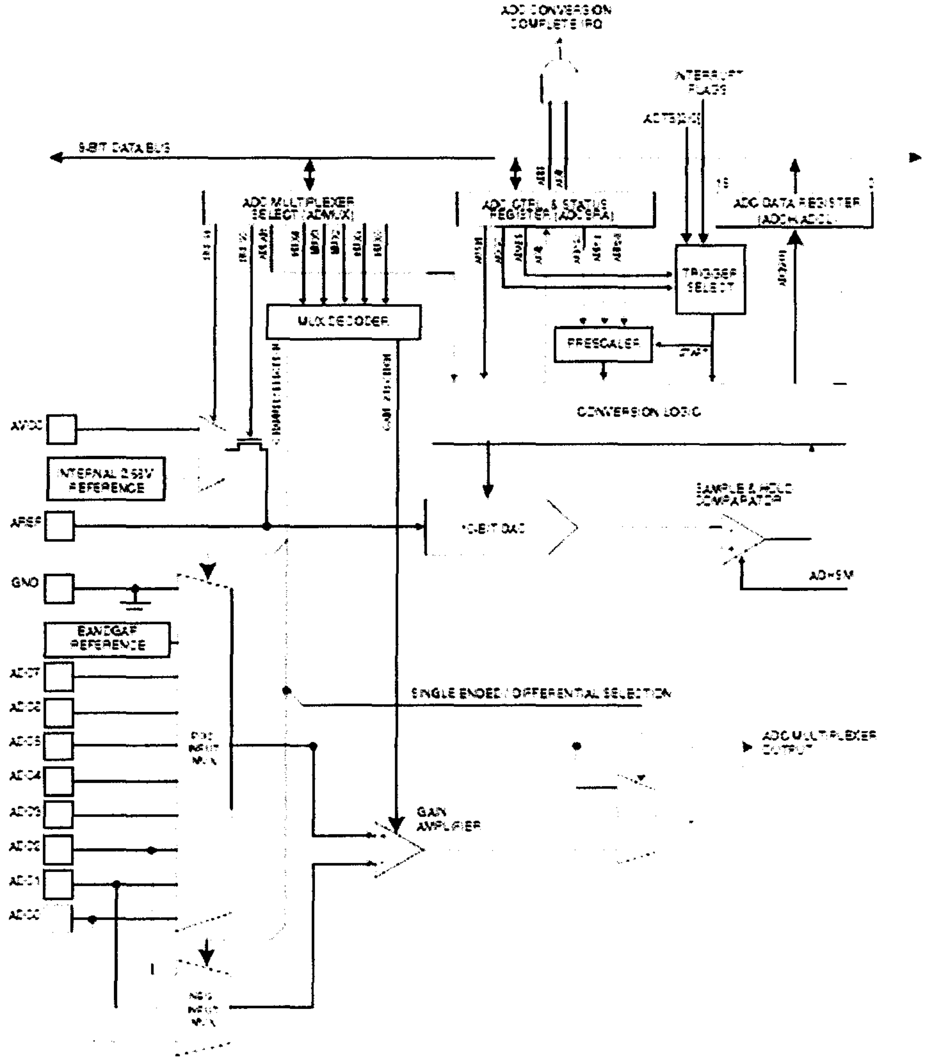


Figure 3-13 Analog to Digital Converter Block Schematic

The ADC has a separate analog supply voltage pin, AVCC. AVCC must not differ more than ±0.3 V from VCC. Internal reference voltages of nominally 2.56V or AVCC are provided On-chip. The voltage reference may be externally decoupled at the AREF pin by a capacitor for better noise performance.

The ADC AVCC was used as the reference and was directly connected to the MCU's VCC. The ADC input channels, ADC1 (pin A1) and ADC3 (pin A3) were connected to one of each of the two Cds Photosensors lead respectively. The other leads were also connected to the ADC0 (pin A0) and ADC2 (pin A2) respectively. The analog input channel was selected by writing to the MUX bits in ADMUX. The ADC input pins, as well as GND and a fixed band gap voltage reference, were selected as single ended inputs to the ADC. The ADC was enabled by setting the ADC Enable bit, ADEN in ADCSRA after the Voltage reference and input channel selections. The ADC generates a 10-bit result which is presented in the ADC Data Registers, ADCH and ADCL. The result was presented left adjusted by setting the ADLAR bit in ADMUX register because no more than 8-bit precision is required. This adjustment allows just the high bytes of the converted signal value contained in ADCH to be read.

A single conversion was started by writing a logical one to the ADC Start Conversion bit, ADSC. This bit stays high as long as the conversion is in progress and will be cleared by hardware when the conversion is completed. The ADC has its own interrupt which can be triggered when a conversion completes. For single ended conversion, the result is

$$ADC = V_{IN} * 1024 / V_{REF}$$

The ADC module contains a prescaler, which generates an acceptable ADC clock frequency from any CPU frequency above 100 kHz. The prescaling is set by the ADPS bits in ADCSRA. The prescaler starts counting from the moment the ADC is switched on by setting the ADEN bit in ADCSRA. The prescaler keeps running for as long as the ADEN bit is set, and is continuously reset when ADEN is low. The ADC prescaler unit is shown in figure 3-14 and its selection table at Table 3-5.

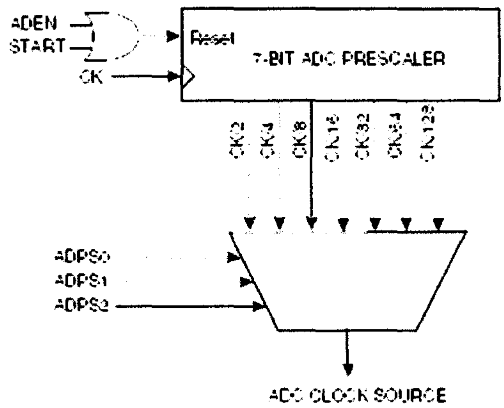


Figure 3-14 ADC prescaler unit

Table 3-5- ADC prescaler selection table.

ADPS2	ADPS1	ADPS0	Division Factor
0	0	0	2
0	0	1	2
0	1	0	4
0	1	1	8
1	0	0	16
1	0	1	32
1	1	0	64
1	1	1	128

The ADPS2 and ADPS1 were set in order to sample the photosensors at 62.5 KHz ($F_{CPU}/64$).

SOFTWARE

The control program was written in C (rather than assembly language) because the program requires math functions not directly supported in AVR assembler, and speed is not much of an issue. The sensors were sample 62.5K times per second, and the processor was configured to run at 4MHz, therefore only about 64 cycles were available to compute and process it before the next input comes in.

The main program initializes the system and then goes into an endless wait loop. Everything happens on the loop unless when an interrupt is triggered. Timer 0 and 1 runs off an internal 4MHz resonator. Other than that, the software architecture is straightforward, just a linear sequence of commands as illustrated in flow chart of figure 3-15. For details see the code listing (with comments in Appendix C).

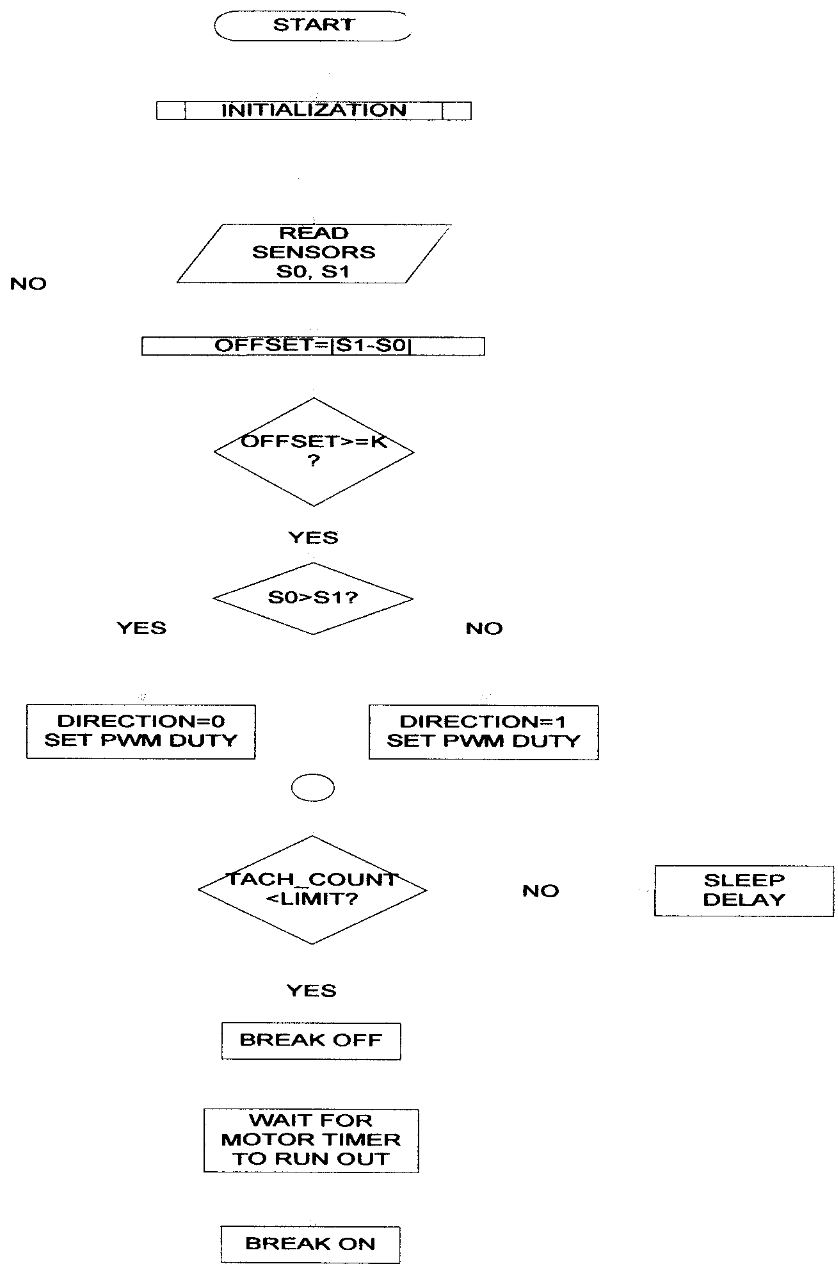


Figure 3-15 Program Flow Chart.

When in operation, point 'D' undergoes an angular displacement of over 90°. This effectively covers the sun path.

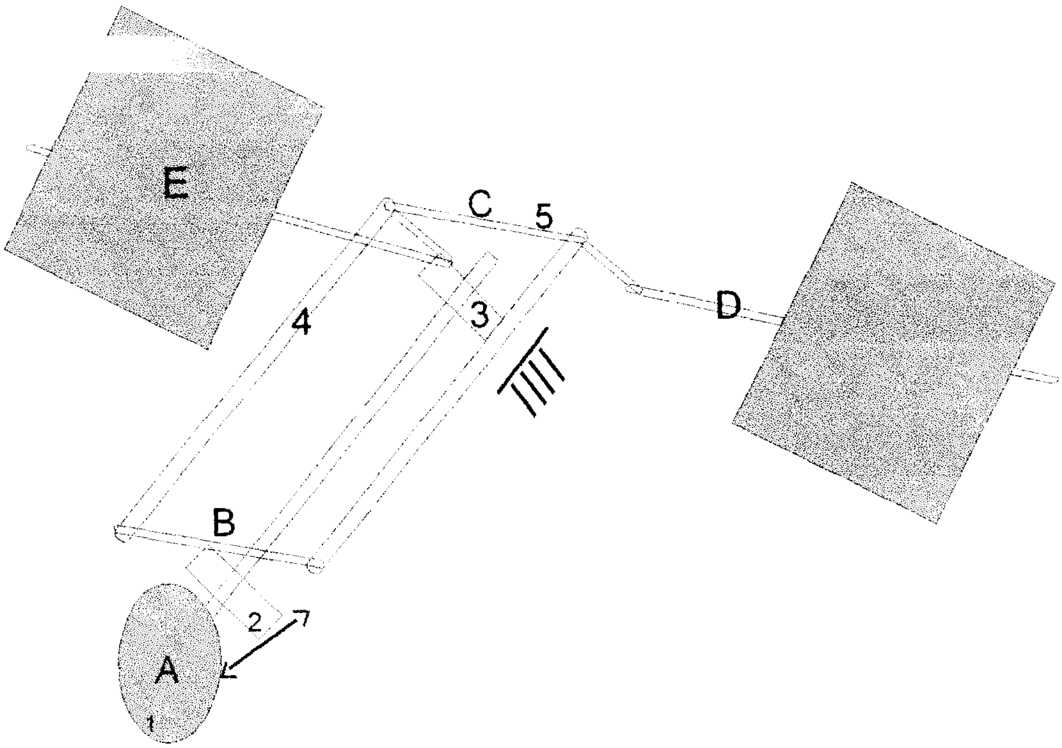


Figure 3.18 Structure of Mechanical support.

1. Motor
2. Gear
3. Worm
4. Links
5. Crank & Shaft

3.4 Design and Construction of the Mechanical Support

3.4.1. Design of a suitable structure.

A large component of the project was the design of a support structure for the solar panels. The design of the support structure has several stringent constraints:

1. The design must be able to support two solar panels.

2. The support structure must allow movement in two axes. The system must be capable of at least 180 degrees of rotation about the horizon, and 90 degrees of vertical adjustment. This range of motion will allow the solar panels to be moved into the correct position at any time during a day.

3. It must be balanced. In order to keep the power consumption of the motors to a minimum, the entire support structure must be balanced about its axes of rotation.

4. The structure must be able to resist significant force from wind. The two solar panels yield a combined surface area of 1.3 m2, which results in large wind loads. Also, one of the best positions for such a device may be on top of buildings. While there may not be as many shadows or obstructions on top of buildings, the wind is usually stronger, which means that the support structure must be able to withstand these harsh conditions without tipping over. As well, the panels must not move because of the wind, which would cause the panels to move from an optimal position.

3.4.2. Construction:

In order to meet the requirements above for a suitable support structure, a link-mechanism system was interwoven with a worm gear system to create a balanced platform as shown.

3.4.2.1 The Link Mechanism.

The function of a link mechanism is to produce rotating, oscillating, or reciprocating motion from the rotation of a crank or *vice versa*. Stated more specifically linkages may be used to convert:

1. Continuous rotation into continuous rotation, with a constant or variable angular velocity ratio.
2. Continuous rotation into oscillation or reciprocation (or the reverse), with a constant or variable velocity ratio.
3. Oscillation into oscillation, or reciprocation into reciprocation, with a constant or variable velocity ratio.

Slider-Crank Mechanism

The four-bar mechanism has some special configurations created by making one or more links infinite in length. The slider-crank (or crank and slider) mechanism below is a four-bar linkage with the slider replacing an infinitely long output link.

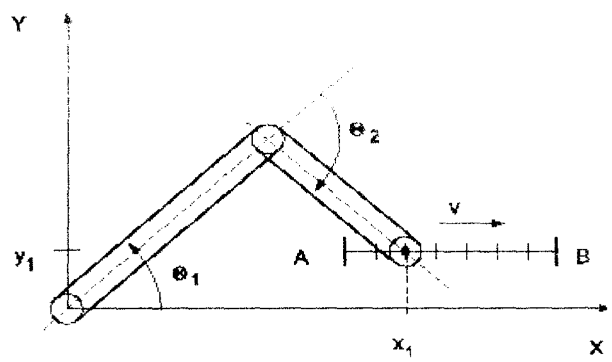


Figure 3.16 Crank and Slider Mechanism

This configuration translates a rotational motion into a translational one. Most mechanisms are driven by motors, and slider-cranks are often used to transform rotary motion into linear motion.

To conveniently calculate the total kinetic energy of each link, it is divided into infinitesimal parts and integrated along the length of each link.

The Kinetic energy of a mass m moving with velocity v is $(1/2)mv^2$. Thus the total kinetic energy of a link can be obtained from

$$K = \frac{m}{2l} \int_0^l v^2(s)\, ds$$

Where s is the distance along the link and v(s) is the velocity located a distance s from one end assuming that all the mass is concentrated along a line and is distributed uniformly from one end to the other with linear density m/l. [11]

In general, v(s) is of the form

$V^2(s) = a + bs + cs^2$

Then clearly,

$K = (m/2l)\,[al + bl^2/2 + cl^3/3]$

3.4.2.2. The Worm Gear

Gears are used in most mechanical devices. They do several important jobs, but most important, they provide a **gear reduction** in motorized equipment.

The small dc motor spins very fast and can provide enough **power** for the device, but not enough **torque**. The motor only produces a small amount of torque at a high speed. With a gear reduction, the output speed can be reduced while the torque is increased.

Another thing the gear does is adjust the direction of rotation.

There are a lot of intricacies in the different types of gears. However the worm gear was employed in this project due to the property discussed below.

Worm Gear drives are the smoothest and quietest form of gearing when properly applied and maintained. They were considered for the following requirements:

- HIGH RATIO SPEED REDUCTION
- LIMITED SPACE
- RIGHT ANGLE (NON-INTERSECTING) SHAFTS
- GOOD RESISTANCE TO BACK DRIVING

A Worm gear was used due to its large gear reductions. It is common for worm gears to have reductions of 20:1, and even up to 300:1 or greater.

Many worm gears have an interesting property that no other gear set has: the worm can easily turn the gear, but the gear cannot turn the worm. This is because the angle on the worm is so shallow that when the gear tries to spin it, the friction between the gear and the worm holds the worm in place.

This feature was most useful for the structural link system, in which the locking feature acted as a brake for the system when the motor is not turning. [12]

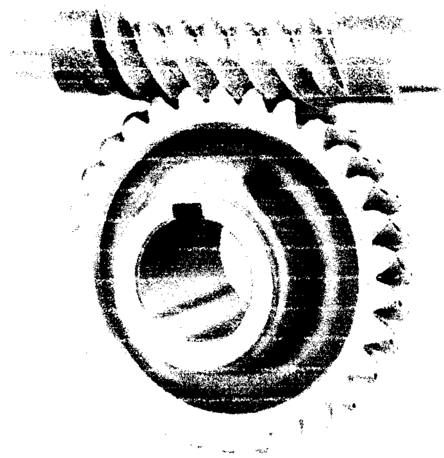


Figure 3.17. Worm gear

3.4.3 The Complete structure

The complete structure was an arrangement of the Link and Gear as shown in figure 3.18

The motor is connected to point 'A'. This spins the worm at a high speed. As the worm spins, the rotational motion is translated into a linear motion by the gear.

Since the longer bar of the link system is connected to the gear at point 'B', and because the shorter bar is also connected to a fixed point, the linear motion is transferred from 'B' to point 'C' resulting in an oscillatory motion about point C which in turn is translated to point 'D through a crank shaft mechanism.

The Solar panels are mounted on a base fixed to the shaft along 'D'.

When in operation, point 'D' undergoes an angular displacement of over 90°. This effectively covers the sun path.

When in operation, point 'D' undergoes an angular displacement of over 90°. This effectively covers the sun path.

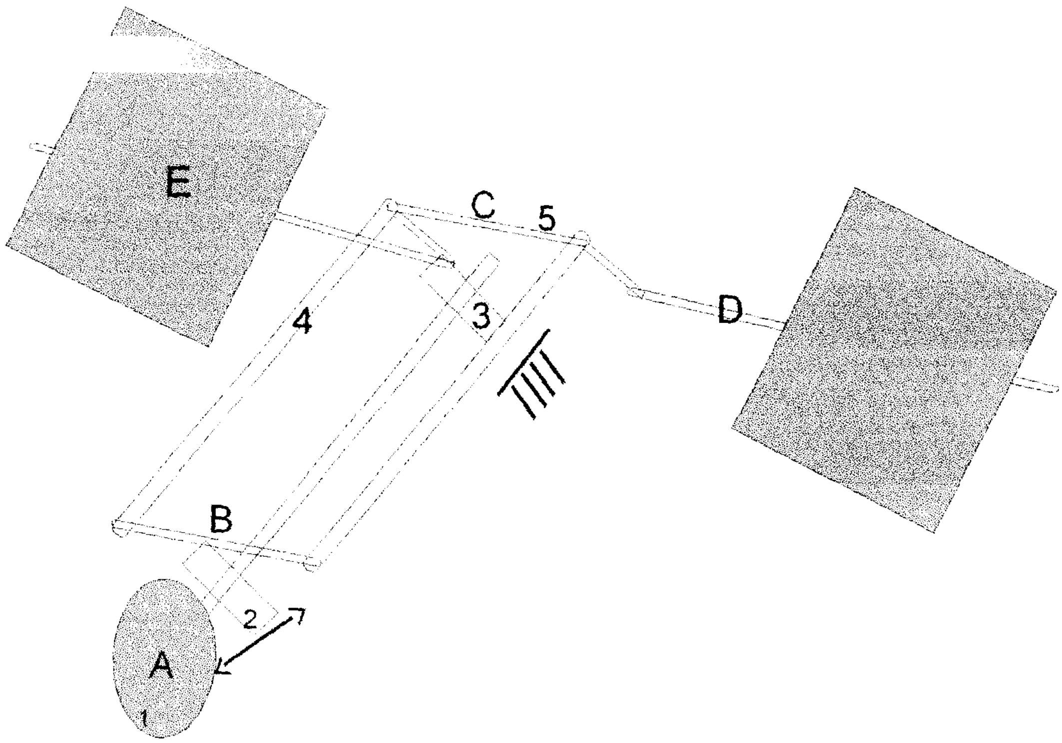


Figure 3.18 Structure of Mechanical support.

1. Motor
2. Gear
3. Worm
4. Links
5. Crank & Shaft

Chapter Four

Construction, Testing and Results

4.1 CONSTRUCTION TOOLS AND MATERIALS

The tools and materials as well as instruments used during the testing and the construction of the project are briefly described below:

(1) **The simulation:** The circuit diagram was tested on the computer using the Multisim 2001 software for the simulation analysis of dc operating points, transients and parameter sweep.

(ii) **The breadboard:** This is a temporary board for circuit testing with tiny sockets that allows for electronic components (i.e. resistors, capacitors, ICs e.t.c) to be plugged in, easily without damaging the component.

The breadboard was used for pre-construction testing of circuit and sub-circuits before the Components were soldered on the Vero board.

(iii) **Analogue / digital multimeter:** These devices (instruments) were used for the Measurement of electrical quantities such as resistance, voltage and current. They were also used to test the circuit sections for continuity. The digital Multimeter gives a digital output display of measured quantities, while the analogue meter gave an indication of the value of measured quantities on a scale, the value of which is read on the position of the pointer on the scale.

(iv) **The Vero board:** This is a perforated board on which electronic components can be inserted and soldered permanently. It was used for the permanent construction of the project prototype from the circuit diagram

(v) Wires and connectors: Wires were used during the testing stage of the project on the breadboard to connect the components together as well as the different sub-units of the circuit, they were also used during the soldering of components on the Vero board. Copper wire was used.

(vi) IC Sockets: This is a device used to hold ICs in position; the IC socket was first soldered on the Vero board before the IC chip was fixed on it to protect the IC from the heat of the soldering iron.

(Vii) Wire cutters / strippers: These tools were used to cut wires to the desired size required before use, as well as to strip off insulation wire in other to expose the conduçtor for proper and neat soldering.

(viii) Soldering Iron: This is a low power heating element typically in range of about 40 Watts. It provides the heat needed to melt the lead, so that it can be used for the connection of the components permanently on the Vero board. It is usually connected to the AC mains.

(ix) Soldering lead: This is a metal (lead) wire of low melting point. It is used to electrically connect components and wires in fixed position on the Vero board.

(x) Lead sucker: This is used to suck up excess molten lead from 'the Vero board to prevent short circuit (bridging) or undesirable electrical connections.

4.2 Construction Details

The circuit was laid-out on the bread board to observe its operational response and ensure that it was in line with required objectives. Then it was dismantled.

The circuit was finally constructed on the Vero board. The components were inserted into the holes on the board properly to ensure that it is out on the other side of the board where the copper tracks are.

All components and connecting wires were inserted in place before soldering. The MCU chip is very sensitive to heat and so was protected by the use of IC socket. The socket was first soldered on the board before inserting the IC.

4.3 Construction Precaution

1. All soldered joints (points) were tested for continuity so as to avoid unnecessary open circuits.
2. All the excess leads were removed to avoid bridges (short circuits) on the boards.
3. Polarities of the electrolytic capacitors and LEDS were properly checked to be correctly positioned before connecting (soldering) on the Vero board.
4. ICs were mounted on 1C sockets to avoid overheating them during soldering by soldering the 1C socket first on the Vero board.
5. Excessive heating of the components was avoided so that they do not burn by making the soldering process to a component very brief.

4.4 Problems Encountered.

1. The specified components were not easily obtainable in the local markets. This resulted in a waste of the limited time for the project as the components had to be complete before commencement.

2. Erratic power supply also slowed down the pace of the project.

3. Limited resources slowed down the mechanical construction of the support structure.

4.5 TESTING AND RESULTS

The circuit was initially constructed on a breadboard and found to be working properly. It was then dismantled, the components were transferred to the Vero board and the connections were made as appropriate. Continuity test was carried out with a multimeter.

The testing of the whole project started with the testing of the power supply unit (12V battery) to ensure that it could supply power to the circuit.

The motor controller circuit was tested next to ensure that it could rotate in the clockwise, anticlockwise as well as stop positions with minimal noise by replicating the action of the microcontroller.

After the whole system units (electrical and mechanical) had been coupled, the solar elevation tracker was then tested as a functional unit and found to be working.

The first test on the solar tracker was carried out with torchlight. When light was directed more on one side, the system was found to adjust to a position that balanced the light on both sensors. The Light was then transferred to the other side to ensure that the system could work both ways. Desired results were obtained with minimal hysteresis. When the light was shown directly, the system was relatively stable.

The same tests were carried out under direct sunlight. The sensors were shaded individually and desired results obtained.

Chapter Five

5.1 Conclusion

From the testing and results obtained, it can be seen that the tracker satisfactorily tracks the sun during the sun hour periods, resets after, and "hibernates" during nighttime and resumes at sunrise the next day. The output of the solar panels is also improved considerably.

The system designed improves the output and thus efficiency of an Amorphous Silicon photovoltaic cell.

The tracker is an option when a higher cell output is required, rather than investing in the increase of more cells, which is by far more expensive.

5.2 Recommendations.

In the design and construction of a Solar Elevation Tracker, the system satisfactorily tracked the elevation of the sun. However due to seasonal changes the system should be expanded to accommodate both elevation as well as lateral tracking.

The system should also be modified to source its own power directly from the sun or from the one generated by the solar panels. Then it would be completely self - driven.

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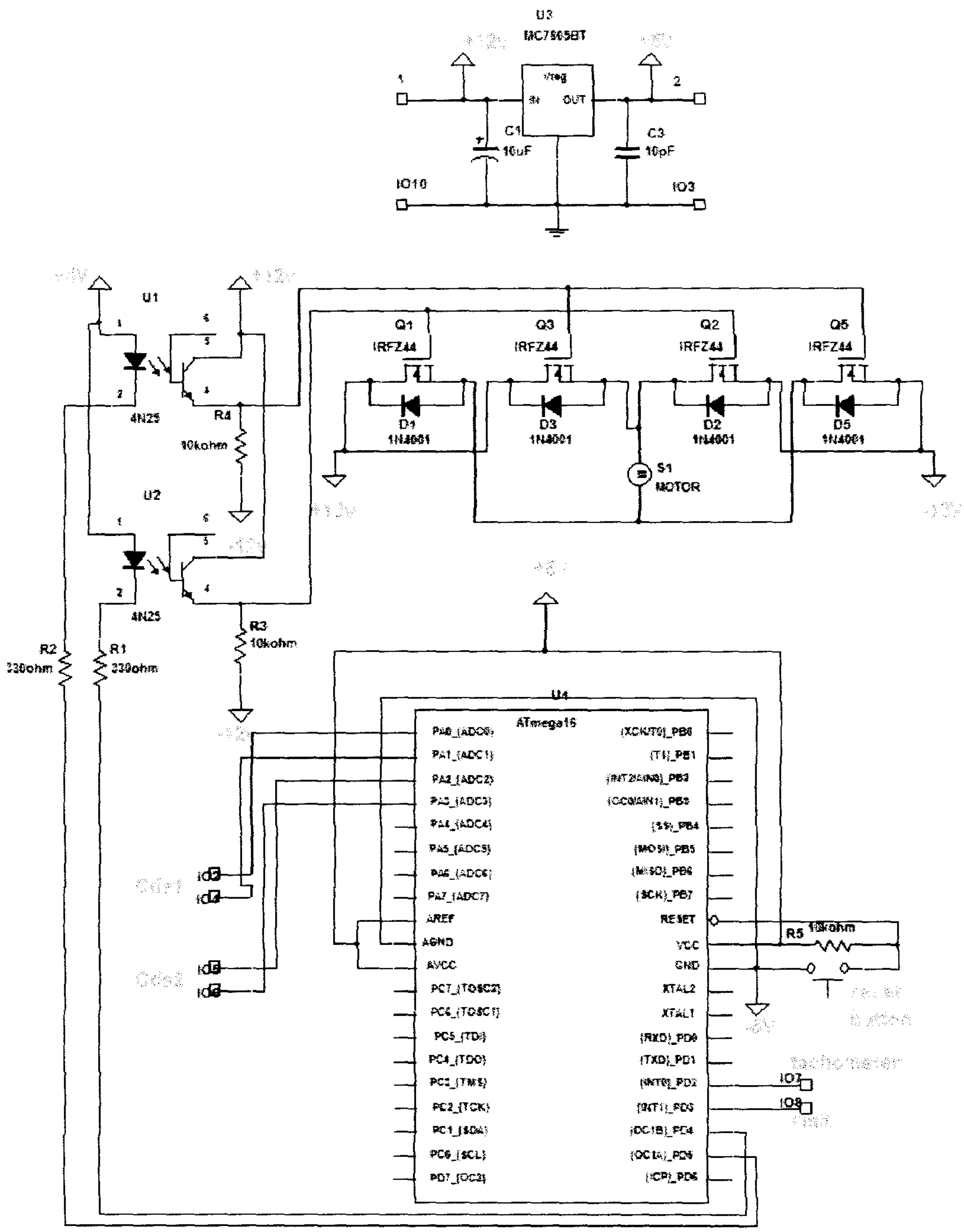
APPENDIX A

Complete circuit diagram



APPENDIX B

Address	Name	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0	Page
$3F ($5F)	SREG	I	T	H	S	V	N	Z	C	7
$3E ($5E)	SPH	–	–	–	–	–	SP10	SP9	SP8	10
$3D ($5D)	SPL	SP7	SP6	SP5	SP4	SP3	SP2	SP1	SP0	10
$3C ($5C)	OCR0	Timer/Counter0 Output Compare Register								80
$3B ($5B)	GICR	INT1	INT0	INT2	–	–	–	IVSEL	IVCE	45, 65
$3A ($5A)	GIFR	INTF1	INTF0	INTF2	–	–	–	–	–	66
$39 ($59)	TIMSK	OCIE2	TOIE2	TICIE1	OCIE1A	OCIE1B	TOIE1	OCIE0	TOIE0	80, 109, 126
$38 ($58)	TIFR	OCF2	TOV2	ICF1	OCF1A	OCF1B	TOV1	OCF0	TOV0	80, 110, 127
$37 ($57)	SPMCR	SPMIE	RWWSB	–	RWWSRE	BLBSET	PGWRT	PGERS	SPMEN	246
$36 ($56)	TWCR	TWINT	TWEA	TWSTA	TWSTO	TWWC	TWEN	–	TWIE	174
$35 ($55)	MCUCR	SM2	SE	SM1	SM0	ISC11	ISC10	ISC01	ISC00	30, 64
$34 ($54)	MCUCSR	JTD	ISC2	–	JTRF	WDRF	BORF	EXTRF	PORF	38, 66, 225
$33 ($53)	TCCR0	FOC0	WGM00	COM01	COM00	WGM01	CS02	CS01	CS00	77
$32 ($52)	TCNT0	Timer/Counter0 (8 Bits)								79
$31[1] ($51)[1]	OSCCAL	Oscillator Calibration Register								29
	OCDR	On-Chip Debug Register								221
$30 ($50)	SFIOR	ADTS2	ADTS1	ADTS0	ADHSM	ACME	PUD	PSR2	PSR10	54,92,128,195,215
$2F ($4F)	TCCR1A	COM1A1	COM1A0	COM1B1	COM1B0	FOC1A	FOC1B	WGM11	WGM10	104
$2E ($4E)	TCCR1B	ICNC1	ICES1	–	WGM13	WGM12	CS12	CS11	CS10	107
$2D ($4D)	TCNT1H	Timer/Counter1 – Counter Register High Byte								108
$2C ($4C)	TCNT1L	Timer/Counter1 – Counter Register Low Byte								108
$2B ($4B)	OCR1AH	Timer/Counter1 – Output Compare Register A High Byte								108
$2A ($4A)	OCR1AL	Timer/Counter1 – Output Compare Register A Low Byte								108
$29 ($49)	OCR1BH	Timer/Counter1 – Output Compare Register B High Byte								108
$28 ($48)	OCR1BL	Timer/Counter1 – Output Compare Register B Low Byte								108
$27 ($47)	ICR1H	Timer/Counter1 – Input Capture Register High Byte								109
$26 ($46)	ICR1L	Timer/Counter1 – Input Capture Register Low Byte								109
$25 ($45)	TCCR2	FOC2	WGM20	COM21	COM20	WGM21	CS22	CS21	CS20	121
$24 ($44)	TCNT2	Timer/Counter2 (8 Bits)								123
$23 ($43)	OCR2	Timer/Counter2 Output Compare Register								124
$22 ($42)	ASSR	–	–	–	–	AS2	TCN2UB	OCR2UB	TCR2UB	124
$21 ($41)	WDTCR	–	–	–	WDTOE	WDE	WDP2	WDP1	WDP0	40
$20[2] ($40)[2]	UBRRH	URSEL	–	–	–	UBRR[11:8]				161
	UCSRC	URSEL	UMSEL	UPM1	UPM0	USBS	UCSZ1	UCSZ0	UCPOL	159
$1F ($3F)	EEARH	–	–	–	–	–	–	–	EEAR8	17
$1E ($3E)	EEARL	EEPROM Address Register Low Byte								17
$1D ($3D)	EEDR	EEPROM Data Register								17
$1C ($3C)	EECR	–	–	–	–	EERIE	EEMWE	EEWE	EERE	17
$1B ($3B)	PORTA	PORTA7	PORTA6	PORTA5	PORTA4	PORTA3	PORTA2	PORTA1	PORTA0	62
$1A ($3A)	DDRA	DDA7	DDA6	DDA5	DDA4	DDA3	DDA2	DDA1	DDA0	62
$19 ($39)	PINA	PINA7	PINA6	PINA5	PINA4	PINA3	PINA2	PINA1	PINA0	62
$18 ($38)	PORTB	PORTB7	PORTB6	PORTB5	PORTB4	PORTB3	PORTB2	PORTB1	PORTB0	62
$17 ($37)	DDRB	DDB7	DDB6	DDB5	DDB4	DDB3	DDB2	DDB1	DDB0	62
$16 ($36)	PINB	PINB7	PINB6	PINB5	PINB4	PINB3	PINB2	PINB1	PINB0	63
$15 ($35)	PORTC	PORTC7	PORTC6	PORTC5	PORTC4	PORTC3	PORTC2	PORTC1	PORTC0	63
$14 ($34)	DDRC	DDC7	DDC6	DDC5	DDC4	DDC3	DDC2	DDC1	DDC0	63
$13 ($33)	PINC	PINC7	PINC6	PINC5	PINC4	PINC3	PINC2	PINC1	PINC0	63
$12 ($32)	PORTD	PORTD7	PORTD6	PORTD5	PORTD4	PORTD3	PORTD2	PORTD1	PORTD0	63
$11 ($31)	DDRD	DDD7	DDD6	DDD5	DDD4	DDD3	DDD2	DDD1	DDD0	63
$10 ($30)	PIND	PIND7	PIND6	PIND5	PIND4	PIND3	PIND2	PIND1	PIND0	63
$0F ($2F)	SPDR	SPI Data Register								135
$0E ($2E)	SPSR	SPIF	WCOL	–	–	–	–	–	SPI2X	134
$0D ($2D)	SPCR	SPIE	SPE	DORD	MSTR	CPOL	CPHA	SPR1	SPR0	133
$0C ($2C)	UDR	USART I/O Data Register								156
$0B ($2B)	UCSRA	RXC	TXC	UDRE	FE	DOR	PE	U2X	MPCM	157
$0A ($2A)	UCSRB	RXCIE	TXCIE	UDRIE	RXEN	TXEN	UCSZ2	RXB8	TXB8	158
$09 ($29)	UBRRL	USART Baud Rate Register Low Byte								161
$08 ($28)	ACSR	ACD	ACBG	ACO	ACI	ACIE	ACIC	ACIS1	ACIS0	196
$07 ($27)	ADMUX	REFS1	REFS0	ADLAR	MUX4	MUX3	MUX2	MUX1	MUX0	211
$06 ($26)	ADCSRA	ADEN	ADSC	ADATE	ADIF	ADIE	ADPS2	ADPS1	ADPS0	213
$05 ($25)	ADCH	ADC Data Register High Byte								214
$04 ($24)	ADCL	ADC Data Register Low Byte								214
$03 ($23)	TWDR	Two-wire Serial Interface Data Register								176

APPENDIX C
Program Code

```
#include <stdio.h>
#include <avr/io.h>
#include <avr/interrupt.h>
#include <avr/signal.h>
#include <avr/pgmspace.h>
#include <avr/sleep.h>

#include <ctype.h>
#include <inttypes.h>
#include <string.h>

#define BAUDRATE 9600
#define BAUD_REG ((uint16_t)((F_CPU / (16.0 * (BAUDRATE))) + 0.5) - 1)    // if
above .5 mark, round up; replace 16 with 8 for double
#define BAUD_H      ((uint8_t)(0xFF&(BAUD_REG>>8)))
#define BAUD_L              ((uint8_t)(0xFF&BAUD_REG))

#define init_motor_period 300               // initial PWM signal period
#define init_motor_duty 150                 // initial PWM duty-cycle period
#defineMOTOR_LIMIT_H  2500
#defineMOTOR_LIMIT_L  100

#defineSID_PORT    PORTA
#defineSID_PIN             PINA
#defineSID_DDR             DDRA

#defineSW_PORT             PORTB
#defineSW_PIN              PINB
#defineSW_DDR              DDRB

#defineLED_PORT    PORTC
#defineLED_PIN             PINC
#defineLED_DDR             DDRC


int                 tach;
uint8_t     limit, direction;       // 1 = left, 0 = right
int         magnitude;
uint8_t     SID[2];
```

```
/*** delay
**********************************************************************
 *      rough delay; 65k loops, 4 instr each, +over head: 65536*4 = 262144,
 *      round up tp 300000 clks (time: 300000/F_CPU seconds)

**************************************************************************
****/
void delay(void) {
        uint8_t i, j;
        for(i=0; i<255; i++) {
                for(j=0; j<255; j++) {
                        asm volatile("nop"::);
                }
        }
}

// Timer 0 Interrupt triggered by Overflow
SIGNAL(SIG_OVERFLOW0) {
        if (motor_timer > 0) { motor_timer--; }
}
/*** SIG_INTERRUPT0
***********************************************************
 *      tachometer

**************************************************************************
****/
SIGNAL (SIG_INTERRUPT0) {
        // a hole has passed on the encoder; increment or decrement the counter
        //      based on the direction
        if(direction == 0)
                tach--;
        else if(direction == 1)
                tach++;

        if(tach >= MOTOR_LIMIT_H)
                limit=1;
        else if(tach <= MOTOR_LIMIT_L)
                limit=0;
        else
                limit=2;
}
/*** SIG_INTERRUPT1
***********************************************************
 *      limit
```

```
*****************************************************************************
****/
SIGNAL (SIG_INTERRUPT1) {
        if(limit == 2)
                limit = 0;
        else
                limit = 2;
        tach = 0;
}
/*** getSID
***********************************************************************
 *      read current position of panels solar intensity detector

*****************************************************************************
****/
void getSID(void) {
        ADCSRA |= _BV(ADEN);                    // enable ADC


        SID[0] = 0;
        ADMUX |= _BV(MUX0);                     // select PA1 as input for ADC
        ADMUX &= ~_BV(MUX1);                            //        "

        ADCSRA |= _BV(ADSC);                                            // start
conversion
        loop_until_bit_is_clear(ADCSRA, ADSC);                  // wait for conversion to
finish

        SID[0] += ADCH;

        SID[1] = 0;
        ADMUX |= _BV(MUX1) | _BV(MUX0);                         // select PA3 as
input for ADC

        ADCSRA |= _BV(ADSC);                                            // start
conversion
        loop_until_bit_is_clear(ADCSRA, ADSC);                  // wait for conversion to
finish

        SID[1] += ADCH;

        ADCSRA &= ~_BV(ADEN);                   // disable ADC


        // excess
```

```
	if(SID[0] > SID[1]) {
		if(SID[1] == 0)
			SID[1]++;
		magnitude = SID[0] / SID[1];
		direction = 0;
	}
	else if(SID[1] > SID[0]) {
		if(SID[0] == 0)
			SID[0]++;
		magnitude = SID[1] / SID[0];
		direction = 1;
	}
	else {
		magnitude = 0;

	}
}
/*** setSpin
*******************************************************************
 *	set speed of motor (PWM)

**************************************************************************
****/
void setSpin(void) {

	if(magnitude < 2) {	// replace # with a hysterisis value
		motor_break();
	else if((direction == 1) && (limit!=1)) {
		PORTD |= _BV(PD4);
		PORTD &= ~_BV(PD5);
		motor_controller(magnitude);
	}
	else if((direction == 0) && (limit!=0)) {
		PORTD |= _BV(PD5);
		PORTD &= ~_BV(PD4);
		motor_controller(magnitude);
	}
	else
		PORTD |= _BV(PD4) | _BV(PD5);
}
}



/*
 * MOTOR FUNCTION: motor_controller(char vel, char dir)
```

```
 */
void motor_controller(int magnitude) {

        // SPEED
        motor_PWM_duty = magnitude*motor_PWM_period/100;
        motor_updateDuty();

        // TIME
        motor_timer = 2; // 0.008 sec interval, 122Hz

// Wait until timer runs out
        while (motor_timer > 0) {}

// break ON
        motor_break();
}
void motor_break() {

        PORTD |= _BV(PD4) | _BV(PD5);
}


/*
 * MOTOR FUNCTION: motor_updateDuty()
 */
void motor_updateDuty() {
        char lowByte;
        char highByte;

        lowByte = (char)(motor_PWM_duty);
        highByte = (char)(motor_PWM_duty >> 8);

        OCR1AH = highByte;
        OCR1AL = lowByte;
}

/*
 * MOTOR FUNCTION: motor_updatePeriod()
 */
void motor_updatePeriod() {
        char lowByte;
        char highByte;

        lowByte = (char)(motor_PWM_period);
        highByte = (char)(motor_PWM_period >> 8);
```

```
	ICR1H = highByte;
	ICR1L = lowByte;
}

/*** SIG_UART_RECV
**************************************************************
 *	interrupt on receive byte; for now just echo if any char received

**************************************************************************
****/
SIGNAL (SIG_UART_RECV) {
	uint8_t temp;
	temp = UDR;				// read
	UDR = temp;			// write (just echo what the user types)
}
/*** uart_tx
*********************************************************************
 *	Transmit given data via UART

**************************************************************************
****/
uint8_t uart_tx(uint8_t uart_tx) {
	while(!(UCSRA & _BV(UDRE)));		// wait for empty tx buffer

	UDR = uart_tx;						// put data in buffer, init
send

	return 0;
}
/*** uart_rx
*********************************************************************
 *	Transmit given data via UART

**************************************************************************
****/
uint8_t uart_rx(void) {
	while(!(UCSRA & _BV(RXC)));		// wait for full rx buffer

	return UDR;					/* return the new c */
}

/*** init
*************************************************************************
 *	init all vars and ports
```

```
****************************************************************************
****/
void init(void) {
	SID_DDR		= 0b00000101;		// sensors (1,3) are inputs, sensor
grounds (0,2) outputs
	SID_PORT	= 0b00001010;		// pull-ups active (1+3), grounding pins low

/*
	PORTD			pullupsdirection
	0 i	RXD		0		0
	1 o	TXD		0		1
	2 i	INT0	1		0			opto-interrupter (rotations)
	3 i	INT1	1		0			opto-interrupter (limit)
	4 o	OC1B	0		1			opto-coupler0 (spin 0)
	5 o	OC1A	0		1			opto-coupler1 (spin 1)
	6 i	ICP		1		0
	7 i	OC2		1		0
*/

	PORTD = 0b11001100;
	DDRD = 0b00110010;
	TCCR0 = 0b00000100;
	TCCR1A = 0b10000010;
	TCCR1B = 0b00011100;
	TIMSK = 0b00000001;

	// set baud rate: UBRR = (F_CPU/(16*BAUDRATE)) - 1
	UBRRH = BAUD_H;
	UBRRL = BAUD_L;
	UCSRB = _BV(RXEN) | _BV(TXEN) | _BV(RXCIE);	// enable tx, rx //and rx
int

	// setup ext. interrupts 0 and 1
	MCUCR |= _BV(ISC11) | _BV(ISC01);	// falling edge
	GICR |= _BV(INT1);			// enable ext int 1

	// setup ADC
	ADCSRA = _BV(ADPS2) | _BV(ADPS1);	// set ADC clock source division (64)
	ADMUX = _BV(ADLAR);			// ADC -> ext ref
voltage


	sei();

	// Global Variables
```

```
        motor_PWM_period = init_motor_period;
        motor_updatePeriod();
        motor_PWM_duty = init_motor_duty;
        motor_updateDuty();
        motor_break();
        motor_timer = 0;

        limit = 2;
        direction = 0;
        magnitude = 5;
        setSpin();
        while(limit != 0) ;
        setSpin();

        GICR &= ~_BV(INT1);                // disable ext int 1 (for calibration only)
        GICR |= _BV(INT0);                 // enable ext int 0 (tach)

        limit = 2;
        direction = 1;
        magnitude = 5;
        tach = 0;
        setSpin();
        while(tach < MOTOR_LIMIT_L) ;

}
int main(void) {
        init();

        fdevopen(uart_tx, uart_rx, 0);
        printf_P(PSTR("\n\r\n\r\n\rHello World!\n\r\n\r"));

        delay();

        // loop forever
    for(;;) {
                getSID();
                setSpin();
        }
}
```

APPENDIX D