Palestine Polytechnic University

College of Engineering and Technology

Electrical and Computer Engineering Department

**Graduation Project**

# Design, build and operation of automatic wood carving and decoration machine

**Project Team**

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According to the orientations of the supervisor on the project and the examined committee is by the agreement of a staffers all, sending in this project to the electrical and computer engineering department are in the college of the engineering and the technology by the requirements of the department for the step of the bachelor's degree.

Project supervisor signature

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Committee signature

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Department head signature

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# Dedication

We dedicate this project:

To our parents

To our brothers

To our friends

To our teachers

To our nation

To our lovely country Palestine

# Acknowledgment


First and for most we should offer our thanks, obedience and gratitude to Allah.

Our appreciation to:

*Palestine Polytechnic University*

*College of Engineering and Technology*

*Electrical and Computer Engineering Department*

*Our supervisor Dr. Abdel-Karim Daud for his helps and support*

*To Dr. Yousef Al-Switi*

*To Eng. Fida'a Al-Jaafrih*

*To any one whom helped us.*

# Abstract

The automatic wood carving and decoration machine is considering all technology that the human was discovered, since it collects between several of techniques: electrical, computer, and mechanical techniques.

The automatic wood carving and decoration machine operations based on carve and decorate the wood automatically using some of a high technology controller was discovered.

The reasons of using the automatic wood carving and decorating instead of manual operation which consider more cheap, that the process become difficult, don’t satisfy the ask of accuracy and consume along of time, so that the process must be automated.

To satisfy the automatic operation, one type of controller like, PC, PLC, and microprocessor can be used, the comparison between these controllers is taken from many aspects i.e. ease of control, time response, range of control for speed and position.

Since the use of the computer is flexible and make the control of the machine more safety, easier, faster, beside that the wood carving and decoration need high accuracy, difficult time response, high range for speed and position control, and control of three dimensions, it is represented as the ask controller, by this we reached the highest technical machine which is the computer numeric control (CNC).

The plant (machine) consists of (in general) four motor, sensors. Three of the motor use to control the moving of the drilling (cutting) that used to carve the wood in the three direction; one for X-axis, the second for Y-axis, and the third for Z-axis,

the forth motor that is an AC synchronous motor used to rotate cutting part. The moving of the motors is restricted in specific range determined by the sensors.

The schematic of the Automatic wood carving and decoration machine is shown in Figure1 and Figure 2:

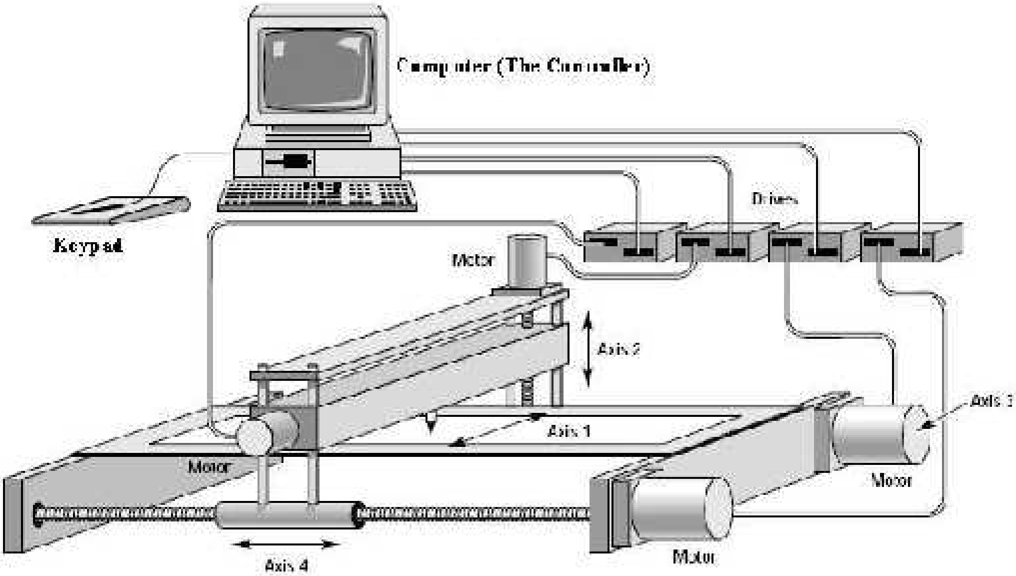



Figure 1: Automatic wood carving and decoration machine

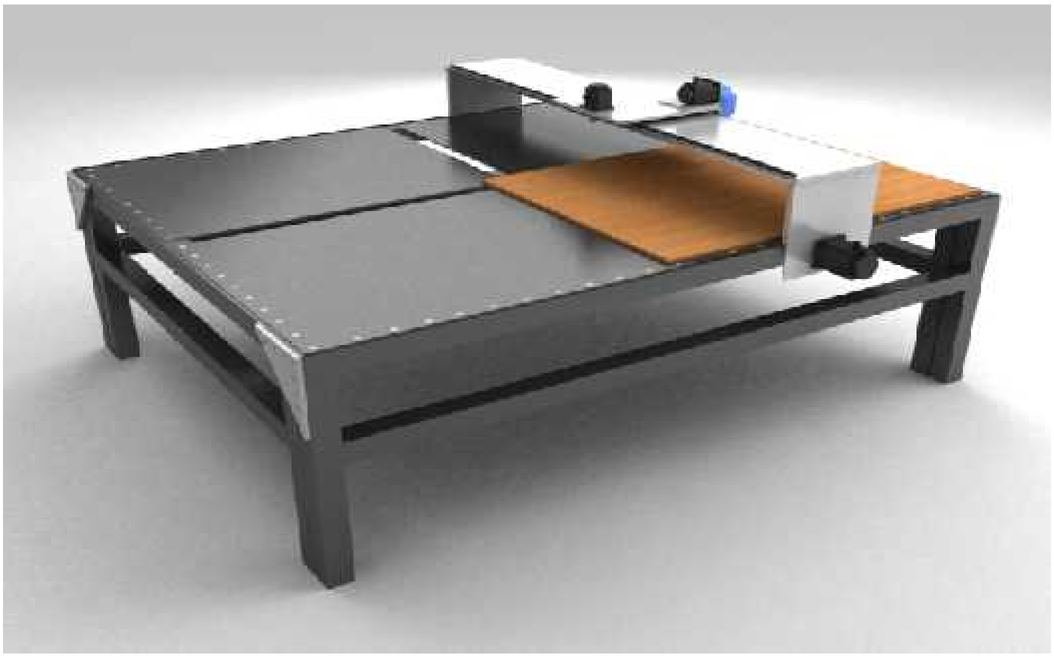


Figure 2: The body of automatic wood carving and decoration machine

# Index

## List of Figures

# List of Tables

# Chapter 1
# Introduction

Invention of the semiconductor components like: diodes, and transistors which are the central components used to process the electrical signals that arise in communication, computation, and control systems, and using it in developing some important devices such as: computers, microprocessors, programmable logic devices (PLC’s) which become used in automatic control process and so resulted in improvement the industry and industrial automation.

With this huge advance there are many types of controller, the compression of it takes from many aspects, i.e. ease of control, time response, and range of control of speed and position.

Automatic wood carving and decoration machine needs fast response, high range of control of speed and position, and complex control techniques; so the controller that is used in it is the computer, which makes it representing the all technology that the human has been reached.

## 1.1 General description of the project:

The machine operation based on: using a free drawing subprogram (on the computer), which gives the user the capability to draw any three dimensional shape, then the operating machine receives the information from the computer through an interfacing circuit and carving the request shape on the wood.

## 1.2 Project selection

- ✓ The project makes the woodcarving and decoration safely, faster, easier, and more accurate.
- ✓ We can carve decorate any shape on the wood using this machine.
- ✓ To meet the needs of the Palestinians market in the field of industry.

## 1.3 Previous studies

There is lake in researches and papers considered CNC machine and servo motor. The literature review describes of this title are mainly in form of papers, sections in textbooks, projects, and Internet sources.

In internet sources we found many projects about servomotor and stepper motor used in different applications such as " Engraving CNC machine ", " Fluted-Bit Cutting Machine" and optical scanner.

## 1.4 Time plan

1$^{st}$ week to 8$^{th}$ week we studied the project and collected data from the Internet and books about the machine and its components, from 8$^{th}$ week to 14$^{th}$ week we wrote some of the documentation, and we made a simulation of the project, and from 16$^{th}$ to 30$^{th}$ we built the machine hardware and complete the documentation and the simulation. Table 1.1 explains the time plan.

Table 1.1: Time plan

| # Weeks | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Collecting data about the machine and its components and understanding it. | | | | | | | | | | | | | | | |
| Write some of the documentation and simulating the project. | | | | | | | | | | | | | | | |
| # Weeks | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| Building hardware of the machine | | | | | | | | | | | | | | | |
| Performing the simulation programs | | | | | | | | | | | | | | | |
| Experiments and testing to the machine operations. | | | | | | | | | | | | | | | |
| Complete the Documentation | | | | | | | | | | | | | | | |

**1.5 Finance study**

The estimated cost of project listed in table 1.2:

Table 1.2: The estimated cost of the project

| Part | Cost ($) |
|---|---|
| **AC servo motors systems (3)** | **6000** |
| **AC synchronous motor** | **340** |
| **Slides (6)** | **5000** |
| **Linear bearings (10)** | **875** |
| **Pinions (3)** | **45** |
| **Work plan iron** | **900** |
| **Profiles** | **630** |
| **Screws** | **200** |
| **Connecting Wires ladders** | **166** |
| **Transformer, cables** | **5000** |
| **Racks (6m)** | **280** |
| **Painting** | **1000** |
| **Milling operation** | **3000** |
| **Computer (P4)** | **500** |
| **Amplifier and voltage decreasing  circuits** | **100** |
| **Interfacing circuit** | **100** |
| **Total cost** | **$24136** |

# Chapter 2
# CNC Machines

## 2.1 Introduction

The appearance of numeric control technique as a root conversion in the way of machines controlling, as a response to the limitation of the machine capability, which results in heavy chains and limitations on the engineering designs and its progressively requirements due to the degree of accuracy and complexity.

And before the beginning of dealing with this technique, it's necessary to introduce the frame where CNC machines work, and when its usage is useful due to the economical side.

Definition of Automation: it is a technique specialized in applying mechanical system, electronics system, and systems, which use the computer to operate the production operations controlling it.

The automation can be divided in the following three types:

1. Fixed Automation:

It is a system in which the sequence of operations is constant in respect to the nature of the composition of production machine itself. This type of automation is controlled by the human and uses a simple electrical control circuit, and it couldn’t accept any variation in the work (to make this variation, the control circuit must be changed).

2. Programmable automation:

It is a system in which the production machines are designed with capability to change the sequence of its operations, The control of these sequence operations is done using a special program, and this makes the machine that uses this type of automation able to produce various shapes (the control of the sequence of operation is done using a special program).

3. Flexible Automation:

It is an extension to the programmable automation system; that is no time lost in doing the programmable process again (change over from one product to another), this type of machines uses the numeric control, which is applied to couple between the computer technique and electronics technique in industrial controlling field.

Definition of a numeric control systems and a comparison between them:

1- Numeric Control (NC):

It’s one of the programmable automation forms; it controls the manufacturing apparatus by using a special program. When the work piece is changed, the program will be changed too, this makes this type of machines is suitable to low and medium production.

An example on this type of machines is the milling machines, and assembly machines.

The basic rule in operating this type of machines is the control of the cutting part position with respect to the work piece.

2- Computer Numeric Control (CNC):

It's a numeric control system using the computer (has a memory to save the programs) to control the machine; the computer is considered as the main part in CNC machines. The CNC machine can be directly programmed using the keyboard of the computer, or by using a punched tape that the computer reads.

The CNC product is not as accurate as the NC product, but it's faster in operating as program transfer prompts to the control unit.

3- Direct Numeric Control (DNC):

It's a manufacturing system contains of one computer; this computer is directly controls several machines, that a particular work piece program is transferred from the computer directly to the numeric control machine.

**2.2 The comparison between the CNC and traditional machines**

The general form of the CNC machines is similar to the traditional machines but there is a basic difference in the source, which required moving the machine in different directions. If wee took the traditional machine we find that there is one motor in it, but the CNC machine contain more than one motor, which control the various movements.

The CNC machine motors control by one computer, but in the traditional machine, moving the machine in the different directions is done manually or mechanically, so the operation process accuracy depends on the worker skills, but in the CNC machines depends on control system type and its capability. We can summarize the comparison between the CNC and traditional machines as in table 2.1:

Table 2.1 shows the comparison between the traditional and CNC machines:

| Contrast field | Traditional machine | CNC machine |
|---|---|---|
| The General form | Like the CNC machine | Like the traditional machine |
| Some of design details:<br><br>a. Structure | <br><br>More soft than the CNC | <br><br>More hard than the traditional machine. |
| b. Motion source | One AC motor. | Special motor to each direction of motion called (Servo motors) from the family of stepper or hydraulic motors. |
| Operation process accuracy | Reaches to 0.01 mm and depends on the worker skills. | Reaches to about 0.01 mm and depends on control system type and its capability. |
| The cost | Relatively low | High, reaches to about 5 times than the traditional one. |
| Motion control | Manually or mechanically | Numeric control program. |

## 2.3 Economical advantages and disadvantages to CNC machines

There are many reasons to the bulky usage of CNC machines in industry. The CNC machine reduces the cost of production to the industries which characterized with a low production amount such as construction of the auxiliary parts required in aircraft industry, hydraulics circuit parts, and CNC machine itself.

The use of the CNC machine in the previous industries satisfies the following utilities:

- ✓ Reduce the time loss without actual production to the machine.
- ✓ Using fixture equipments more simple than the traditional machine used.
- ✓ The flexibility in the production process.
- ✓ Accept the changes in bits design as these needs to change only the bit program.
- ✓ Increase the manufacturing accuracy and reduce the workers mistakes.

The preceding discussion shows that the CNC machines are suitable in particular cases; we can conclude that the operation process that gives economical benefits has the following properties:

1- Small and medium pieces which continuously produced.
2- Complex pieces engineering according to the shape.
3- Operating the pieces needs a number of processes.
4- Large amount of rapish.
5- Design changes are expected.
6- The pieces have high cost; this is shown especially when manufacturing mistakes are occurred.
7- Needs to the best production.

But the use of CNC machines in a plant results in the following problems:

- Increasing the electrical maintenance in the plant.
- The initial cost to the CNC is rising.

- Machine operating cost is rising.
- Training the worker to understand the CNC system, its programming, its operation, and its maintenance.

## 2.4 CNC motion types

The CNC machines can be categorized in the following three groups (with respect to control type in relative motion between the cutter part and the work piece):

1. Positional control machines (point to point).
2. Linear path control machines (straight cut).
3. Continuous (contouring) control machines.

The menu mentioned above is arranged progressively with respect to the complexity level and the modernity of the system, that means that the contouring control machines is the most developed type.

(1) The positional control (point to point):

The aim of this type of control is to move the cutting part to a location determined previously without the importance of the speed or the path that the cutting part follows to reach this location, and when the cutting part reaches the requested location, the machining operation starts at that location, and no machining will occur until the required motion is completed.

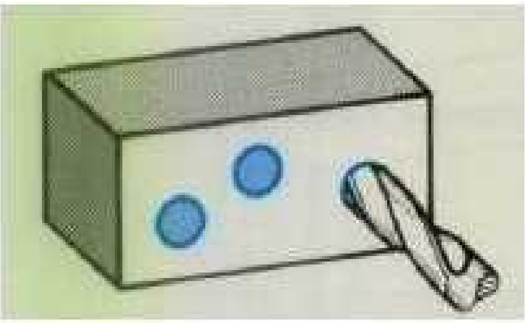


Figure 2.1: The positional control

The best example for this type of control is computer numeric control of drilling machines.

In spite of the lack of importance of the path that the cutting part follows to reach the point of operation, we have to make a complete certainty of programming process to avoid the shocking between the cutting part and the work piece or the fixing preparation, which fixes the piece.

This controlling system is the simplest one, and so it is considered to be the cheapest of the three types mentioned above.

Usually in such a system we find that the supplying power and speeds of the cutting part with respect to the work piece is controlled by the worker of the factor more than the program, which is prepared for the work piece.

And the speed which the cutting part moves to the required location between 5.000 and 10.000 mm / min., according to the abilities of numeric control machine.

(2) Linear path control machine (straight - cut):

Those systems are characterized with the ability of moving of the cutter part in parallel to any of the principal axes with a controlled speed which is suitable for operation, and machines of this type has a positional controlling ability. An example of this type is the sorting CNC machines, which can be used in drilling machines. In such a system we can't get more than one movement at a time in different axes, and so we cant execute straight cutting processes in an incline direction (with an angle) on any of the principal axes. The last statement is true if we took only the traditional definition of the linear path control machines, but if we treated with the non-traditional definition (which means the ability of a control system to move the cutting part in two different axes at the same time) and so we can execute straight cutting process in an incline direction on the principal axes.

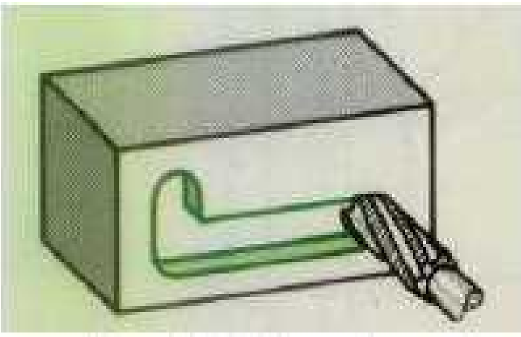


Figure 2.2: The linear path control

(3) Continuous path control (contouring):

This type of controlling types is the most complex, flexible, and highest cost, and contains inside it the abilities of the previous two types of control, in addition to its recognizable property, that it has the ability of movement controlling in more than one axis at a time, thus, in this system getting movement in a straight direction or in an incline direction with an angle, or circular and conic paths and any curve that can be defined with an certain arithmetic formula can be achieved.

An example of this type of motion control which is used in milling and engraving machines.

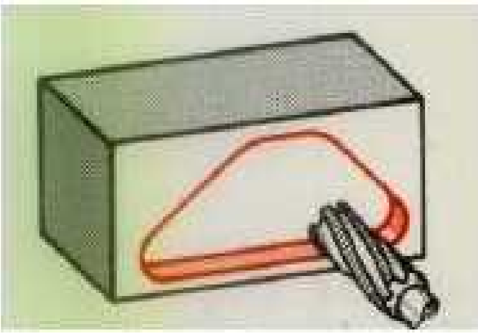


Figure 2.3: The continuous path control

The non-traditional definition of this system is its ability to move the cutting part in more than one axis at a time.

Classification of CNC machines according to the number of controlling axes in a continuous path:

CNC machines classification in the past stimulated problems and doubts, that’s because it was established only in respect to the type of the continuous controlling. And machines which operating a control in two axes (known as 2D) which means two dimensions, and if that control was in three axes (known as 3D), whereas if the machine of that control was in two axes and the third axis supply is controlled to reach a specified location, means that it has a linear path controlling (known as 2.5D).

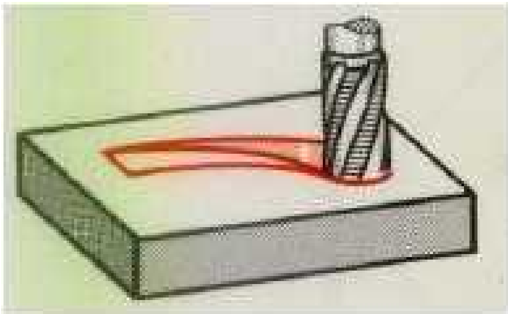


Figure 2.4: Three dimension contouring control

And to vanish those problems, classification system was created, which takes in consideration the control type whatever it was, and also the number of axes it works on, thus, the positional control was symbolized as (P), linear control as (L), and continuous control as (C), then, instead of calling it as (2.5D), it can be called as (2C, L).

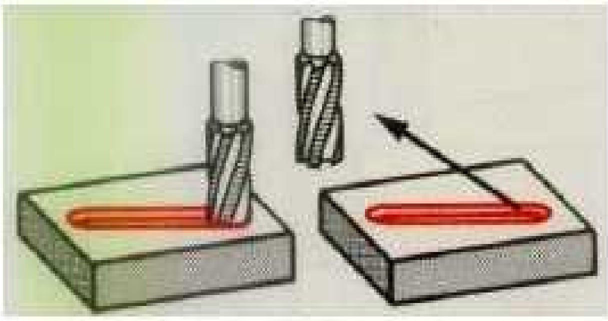


Figure 2.5: (2C, L) control

From the previous discussion we can classify the Automatic Wood Carving and Decorating Machine as (2C, L) CNC machine.

# Chapter 3
# Machine block diagram

## 3.1 Introduction

The automatic wood carving and decorating machine system configuration is closed loop, so before discussion its block diagram we show the comparison between the two control systems configuration: open loop and closed loop.

Definition of control system: control is a process in a system by which one or more input quantities affect other quantities (output quantities) according to a specific legality (program).

We build control systems for four primary reasons:

1. Power amplification.
2. Remote control.
3. Convenience of input form.
4. Compensation for disturbance.

We now describe the two-control systems configuration: open loop and closed loop, as the following:

## 3.2 Open loop systems

A generic open-loop system is shown in Figure 3.1. It starts with a subsystem called and input transducer, which converts the form of the input to that, used that uses by the controller .The controller drives a process or a plant. The input is sometimes called the reference, while the output can be called the controlled variable. Other signals, such as disturbances, are shown added to the controlled and process outputs via summing junctions, which yield the algebraic sum of their input signals using associated signs. For example, the plant can be a furnace or air conditioning system, where the output variable is temperature .The controller in a heating system consists of fuel valves and the electrical system that operates the valves.

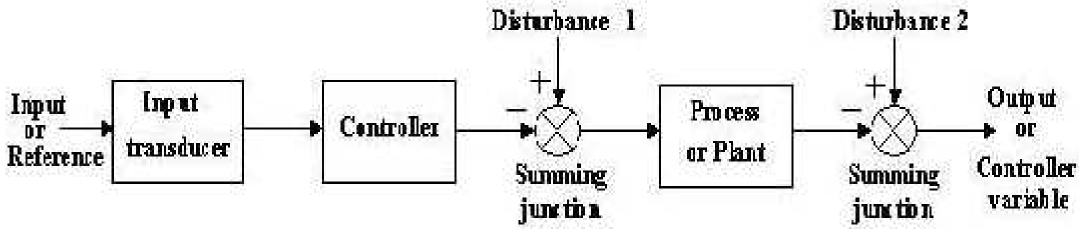



Figure 3.1: Open loop system

The distinguishing characteristic of an open _loop system is that add to the controllers driving signal (Disturbance 1 in Figure 3.1. For example, if the controller is an electronic am-pilfer and Disturbance 1 is noise, then any additive amplifier noise at the first summing junction will also drive the process, corrupting the output with the effect of the noise .The output of an open-loop system is corrupted not only by signals that add to the controllers command but also by disturbances at the output disturbance to the Figure 3.1. The system can't correct for these disturbances, either.

Open-loop systems then do not correct for disturbances and are simply commanded by the input .For example; toasters are open-loop systems, as anyone with burnt toast can attest. The controlled variable (output) of a toaster is the color of the toast. The device is designed with the assumption that the toast will be darker the longer it is subjected to heat. The toaster doesn't measure the color of the toast; it doesn't correct for the fact that the toast is rye, white, or sourdough, nor does it correct for the fact that toast comes in different thick nesses.

Other examples of open-loop systems are mechanical systems consisting of a mass, spring and damper with a constant force positioning the mass. The greater the force, the greater the displacement. Again, the system position will change with a disturbance, such as an additional force, and the system will not detect or correct for the disturbance or assume that you calculate the amount of time you need to study for an examination that covers three chapters in order to get an A. If the professor adds a fourth chapter a disturbance- you are an open-loop system if you do not detect the disturbance and add study time to that previously calculated the result of this oversight would be a lower grade than you expected.

### 3.3 Closed loop (feedback control) systems

The disadvantages of open loop systems, namely sensitivity to disturbance and inability to correct for these disturbances, may be overcome any closed loop systems. The generic architecture of a closed loop system is shown in Figure 3.2.

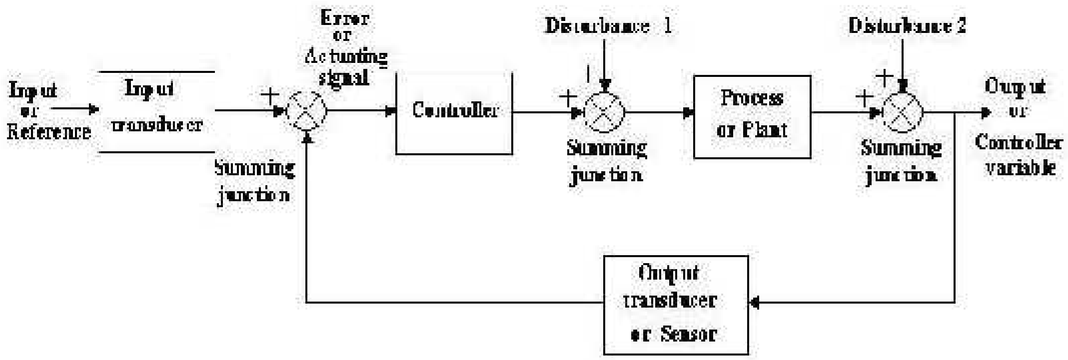



Figure 3.2: Closed loop system

The input transducer converts the form of the input to the form used by the controller. An output transducer, or sensor, measures the output response and converts it into the form used by the controller. For example, if the controller uses electrical signals to operate the valves of a temperature control system, the input position and the output temperature are converted to electrical signals. The input position can be converted to a voltage by a potentiometer, and the output temperature can be converted to a voltage by a thermistor (a device whose electrical resistance changes with temperature).

The first summing junction algebraically adds the signal from the input to the signal from the output, which arrives via the feedback path, the return path from the output to the summing junction. In Figure 3.2, the output signal is subtracted from the input signal. The result is generally called the actuating signal. However, in systems where both the input and the output transducers have unity gain (that is, the transducer amplifies its input by 1), the actuating signal's value is equal to the actual difference between the input and the output. Under this condition, the actuating signal is called the (error).

The closed loop system compensates for disturbances by measuring the output response, feeding that measurement back through a feedback path, and comparing that response to the input at the summing junction. If there is any difference between the tow responses, the system drives the plant, via the actuating the signal, to make a correction. If there is no difference, the system doesn't drive the plant, since the plant's response is already the desired response.

Closed loop systems, then, have the obvious advantage of greater accuracy than open loop systems. They are less sensitive to noise, disturbances, and changes in the environment. Transient response and steady-state error can be controlled more conveniently and with greater flexibility in closed loop systems, often by a simple adjustment of gain (amplification) in the loop and sometimes by redesigning the controller. We refer to the redesign as compensating the system and to the resulting hardware as compensator. On the other hand closed loop systems are more complex and expensive than open loop systems. A standard, open loop toaster serves as an example: it is simple and inexpensive. A closed loop toaster oven is more complex and more expensive since it has to measure both color (through light reflectivity) and humidity inside the toaster oven. Thus, the control systems engineer must consider the trade-off between the simplicity and low cost of an open loop system and the accuracy and higher cost of a closed loop system.

In summary, systems that perform the previously described measurement and correction are called closed loop systems. Systems that don't have this property of measurement and correction are called systems.

### 3.4 Computer controlled systems

In many modern systems, the controller (or compensator) is a digital computer. The advantage of using a computer is that many loops can be controlled or compensated by the same computer through time-sharing. Furthermore, any adjustments of the compensator parameters required, to yield a desired response can be made by changes in software rather than hardware. The computer can also perform supervisory functions, such as scheduling many required applications.

### 3.5 Introduction to project:

The Automatic carving and decoration machine contains of four AC motors; one AC synchronous motor and three AC servo motors(X, Y, and Z), these four motors are controlled automatically by the computer -which include a subdrawing program which give the user the ability to draw any three dimensions shape- and manually by the microcontroller, the information's are transferred from the computer or the microcontroller to the motors through an interfacing circuit and amplifiers.

The power required to operate the AC synchronous motor is directly connected to it from the 3-ph source, but the power required to operate each of the three AC servo motors is connected to them through a transformer.

The sensors in the machine are used to restrict the motors motion in specified rang and to indicate that the wood board is fixed on the correct position on the work plane.

From the previous paragraphs, the machine divided into three major components: Software component, Interfacing circuit, and Hardware component, the following simple block diagram shows the arrangement of these parts, as shown in Figure 3.3:

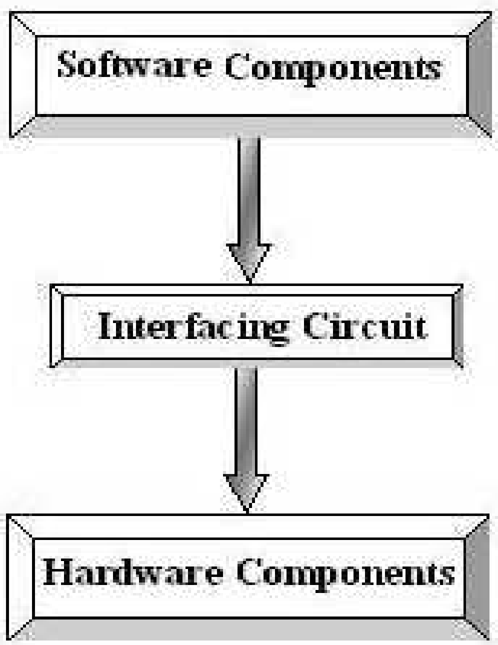



Figure 3.3: Simple block diagram

### 3.6 The general block diagram:

Figure 3.4 shows the automatic wood carving and decorating machine block diagram, that is the controller is the computer, the process is the machine which consist of (in general) four motors, the input is the desired position and speed, the output is the actual position and speed, and the transducer is the six sensors.

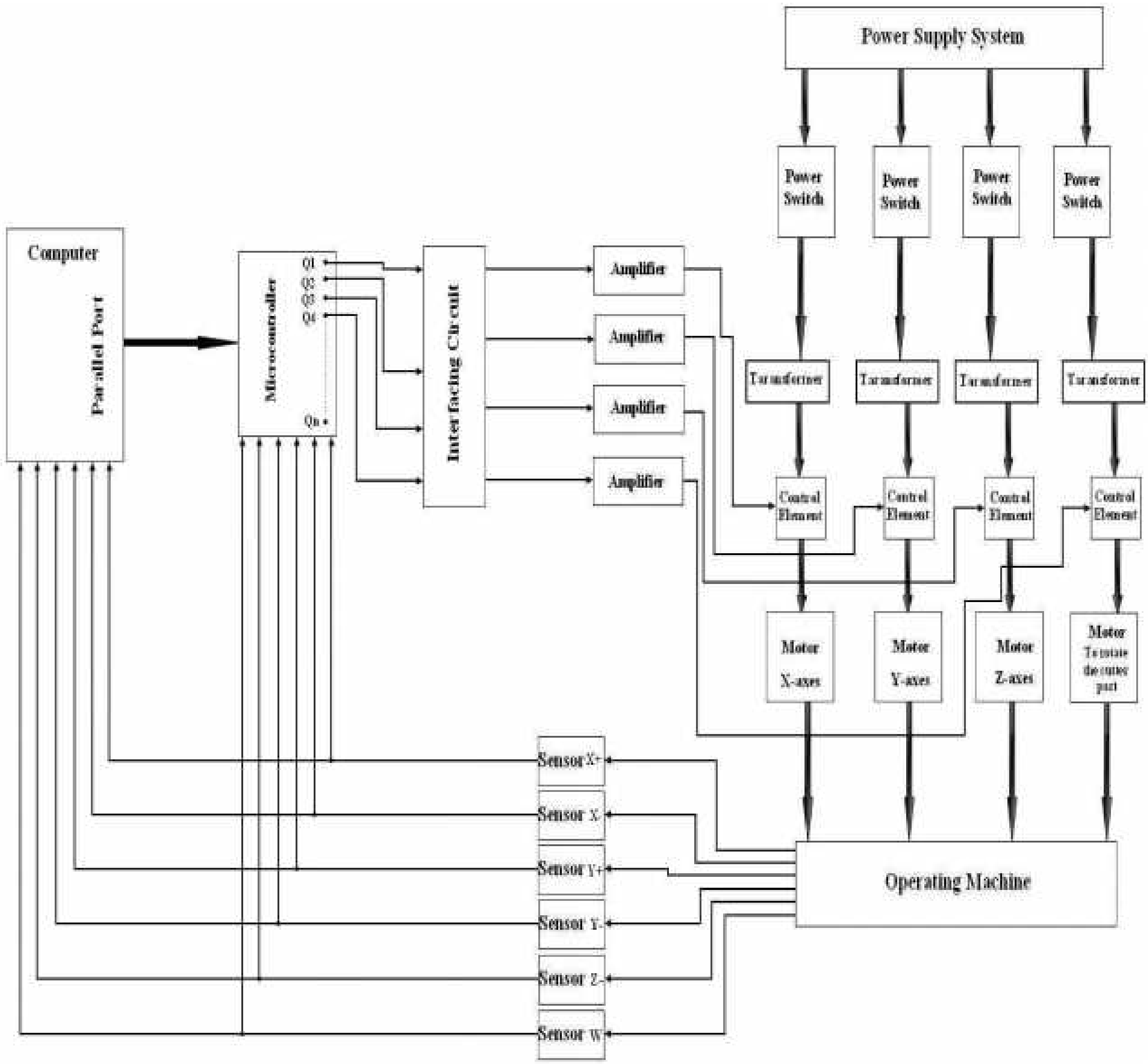



Figure 3.4: General block diagram

The components of the machine block diagram are explained in the following subsections:

### 3.6.1 Servo motors

It is a type of special motors, it is used in the position, speed and torque control, thus is sometimes called a “control motor”.


There are many applications using the servo motor such as: the radar devices, the antennas, the printing devices, and in moving the airplanes wings, from the mentioned applications we can notice that these applications work on low speeds, so the servo motor characterizes in low speeds.

To operate such previous loads the following properties must be existed in the servomotors:

1. Fast response that is the motor speed reaches the rated value (steady state) at once when switching it on with the input supply, also at once stops when disconnecting the supply.
2. The relation between the voltage and the speed is linear to simplify the control system and its components, and to improve it's effectively.
3. The motor accepts connecting and disconnecting operations whatever they repeated.

Thus when designing the servo motor, the previous properties must be existed, for example to obtain the fast response, the value of the rotor moment of inertia must be reduced, and this can be done by reducing the rotor diameter and increasing its length.

The servomotors are classified into tow types: AC servomotors, and DC servomotors, most of these motors depend on the armature control way to satisfy the position control by varying the voltage value.

Each of AC servo and DC servo motors has advantages and disadvantages, for example the DC servo motor characterized with: Linear relation between the voltage versus speed, and between the torque versus the speed; so the control system of them is effective and simple, but it is more expensive, has a higher weight than the AC servo motor, needs the maintenance, and we cant use it in the dangerous places because of sparks they may occur when operating.

The AC servo motor characterized with simple constitution, low cost, and power of endure, but it is a type of high-coupled machines, that the angle between rotor and stator fields isn't (90 º), and the relation between the speed and the voltage and the relation between the speed and the torque isn't linear.

We will use three AC servomotors to operate the machine, one to moving the cutting part in the X-axis, the second is to move the cutting part in the Y-axis, and the third is to move the cutting part in the Z- axis. These motors receive the information that reaches from the computer (the graph that the program performs) through the parallel port or from the microcontroller and perform it on the wood.

The cutting part moves in the X and Y-axes in whole directions but the movement with a specified depth in the Z-axes (one direction).

The digital AC servo system is typically available with six modes. In our project we need to use the position mode after determining the speed of each type of the wood.

### 3.6.2 Synchronous motor

The synchronous motor is a type of the AC motors, and it is called “synchronous” because its speed is directly related to the line frequency:

$$n_s = (120 * f) / P \text{ rev/min} \quad (3.1)$$

Where:

ns: the synchronous speed.
f: the source frequency.
P: number of poles.


In our project we need the synchronous motor to rotate the cutting part process, thus it must be operated when the machine starts its operation and then other motors are operated, and when this motor is turned off, also other motors must be tuned off too.

### 3.6.3 PC controller

The controlling of the machine operation’s would be done using the personal computer, this can be performed by using one of the programming languages like

Java, or visual basic, these languages contain an instruction which goes to the parallel port and to the interfacing circuit, and then we can take them as digital signals.


### 3.6.4 Microcontroller

We would use the microcontroller to control the machine externally by its keypad (we can move the motors of the machine manually using it), and the signal out from the microcontroller goes to the interfacing circuit and to the operating machine through the amplifiers.


### 3.6.5 Amplifier

After we take the digital signal from the interfacing circuit, the signal is represented as voltage of (5 V), and the motor needs to voltage higher than that value to control its operation, so we are used an amplifier to increase the (5V) to a value suitable to the motor.

The transfer function of the amplifier is:

G(s) = Vout / Vin = K……………………………………………………………. (3.2)

Vout = K * Vin……………………………………………………………….... (3.3)

Where:

Vout: is the output voltage of the amplifier.

Vin: is the input voltage of the amplifier.

K: is the gain of the amplifier.

### 3.6.6 The power supply

It is 3-ph (380V) used to supply the machine (the motors) with request power, and it has a switch between it and the motors to turn the motor on or off.


### 3.6.7 The transformer

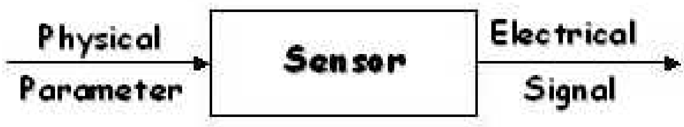
Transformers are used extensively for AC power transmissions, and for various control and indication circuits.

The construction of the transformer is a common iron core with the primary and secondary windings and isolated electromagnetic sheets.


The power required to operate the AC servo motor is 3-Ph (220V) so we need the transformer to transfer the 3-ph AC voltage (380V) to 3-ph AC voltage (220V) to supply the AC servo motors.

### 3.6.8 The sensors

A sensor is a transducer, which converts a physical parameter to an electrical signal.




In our project, we need six sensors situated on different locations on the machine, two of those sensors limits the movement of the motor with respect to the X-axis, the other two sensors limits the movement of the motor with respect to the Y-axis, the fifth sensor indicates that there exists a wood board on the correct position on the machine, the last sensor used in the Z-direction to protect the cutting part movement from going into a wrong depth, which causes a problem in the machine.

Where:

Sensor X+: It is the sensor used to restrict the movement of the X-servo motor in the positive X-direction.

Sensor X-: it is the sensor used to restricted the movement of the X-servo motor in the negative X-direction.

Sensor Y+: It is the sensor used to restrict the movement of the Y-servo motor in the positive Y-direction.

Sensor Y- : It is the sensor used to restrict the movement of the Y-servo motor in the negative Y-direction.

Sensor Z- : It is the sensor used to restrict the movement of the Z-servo motor in the negative Z-direction.

Sensor W: It is the sensor used to indicate that the wood board was putted on the work plane of the machine.

# Chapter 4
# AC servo motor system

## 4.1 Introduction

The main part in the Automatic Wood Carving and Decorating Machine hardware is the motors, which must be used to perform its operation. The servo or stepper motor can be used in the Automatic Wood Carving and Decorating Machine, but we used the servo motor instead of stepper, this refers to the following reasons:

Servos are better because:

1) Dynamic response, accelerate faster when starting and stopping, and changing direction.

2) Easy to setup, plug and play.

3) Always cool to the touch, no thermal effects.

4) More Power, Servo motor torque curve is linear. Full power is available at both low and high rpm.

5) No lost steps, if the motor is asked to position where it cannot (like through a vise), it will fault and stop.

6) Faster feed and rapid speeds.

7) Fault condition stops all axes.

8) Closed loop system always knows where it is located, and following error is less than the accuracy of the machine.

9) Higher resolution than steppers.

Steppers-not because:

1) Much slower acceleration without losing steps.

2) Heat buildup affects machine accuracy and axis linearity.

3) Resonance causes lost steps at certain speeds and cutting loads.

4) Requires slower speeds to avoid losing steps.

5) Much higher voltages required approaching servo speeds, and then thermal losses increase geometrically.

6) Noisy - stepper drivers and motors make an audible hissing and stepping noise.

7) Machine slide and lead screw maintenance is critical as the least bit of sticking, binding, or bumping can cause loss of position.

### 4.1.1 Comparison between servo and stepper motors

The main differences between servo and steeper motors in some of contrast fields is shown in the following:

**1. Maintenance**

Steeper motors: stepper motors are brushless. They experience little or no wear, and are virtually maintenance-free.

Servomotors: brush-type servomotors require a change of brushes, typically, after 5,000 hours of heavy use otherwise they are virtually maintenance free.

**2. Cost**

Steeper motors: in general, stepper motor systems tend to be only slightly less expensive than servo motor systems and the price difference is getting smaller.

Servomotors: Servomotors tend to be 5% to 15% more expensive than similar stepper systems.

**3. Resolution and accuracy**

Steeper motors: for a given screw pitch, typical four phase stepper motors can produce 200 full steps, 400 half steps, and up to 25,000 micro steps per revolution. It is significant to note that since the stepper motor is open loop, it does not necessarily achieve the desired location, especially under load. Particularly poor positional accuracy can result when using micro stepping, which is mostly useful for smoothness of motion.

Servomotors: servo motor resolution depends upon the encoder used. Typical encoders produce 2,000 to 4,000 pulses per revolution, and encoders with up to 10,000 pulses per revolution are available. Since servos are closed loop, they can and do achieve the available resolution and they are able to maintain positional accuracy.

**4. High speed and power**

Steeper motors: steppers have very poor torque characteristics at higher speeds. This condition is improved only slightly by micro stepping; however, unless the stepper is used in a closed loop mode, it does not usually perform as well as a servo. Once the stepper is used in a closed loop mode, it usually becomes more expensive than the servo system of comparable size.

Servomotors: servos can produce speeds and powers two to four times that of similarly sized steppers. This improvement is a direct result of the closed loop (i.e., constant position feedback), which allows for higher speed and greater reliability. The closed loop nature of the servo also allows such a system to better utilize peak torque capabilities.

**5. Open loop compared to closed loop**

Steeper motors: stepper motors are almost always used in an open loop configuration. This means that the motor is commanded to move a certain amount but the computer does not know if the motor has or has not moved that amount. In some cases, resonance or vibrations can cause a stepper motor to lose steps or stall out before completing the motion. This is an ever-present possibility.

Servomotors: by nature, servomotors have constant position feedback from the optical encoder. This device sits on the back of the motor and keeps the controller informed of how far the motor has actually moved. This position feedback is used to correct any discrepancy between a desired and an actual position. This constant corrective action results in faster speeds (up to three times the throughput), and increased power (up to three times the torque) at high speeds. The closed loop nature of the servo also ensures that stalling cannot occur unless there is an immovable object in the path.

## 6. 3D carving and contouring

Steeper motors: steppers can be made to do 3D carving applications but because of the drop in torque at high speeds, they usually have to move slower than servo motors to make sure the motor does not stall or miss steps.

Servomotors: servos can perform high-speed continuous motion much more reliably, making them much better than steppers in three-dimensional contouring applications. We have found time reductions of up to 80% on some applications. The continuous motion also results in better finish quality. In addition, the servo's reliable high-speed continuous motion can reduce the possibility of scorching and melting when working with woods and plastics.

## 4.2 AC servo system torque

Understanding the operation of a high performance dc servo system is an excellent place to begin before we proceed with a discussion of the ac servo system.

### 4.2.1 DC servo motor torque

The control structure for a dc servo system is identical to the ac servo system and the principle of torque production in a dc servo motor will be used to draw the close parallel to torque production in the ac servo motor.

#### 4.2.1.1 Cascade control structure

The most common structure of a high performance dc servo system is shown in Figure 4.1. There is virtually universal agreement that the cascaded control structure is the most effective approach to high performance servo systems. The cascade control structure includes an innermost current (or torque) regulator, a speed regulator around the current (or torque) regulator, and an outermost position regulator around the speed regulator. The sequence of position, speed, and current (torque) is natural as it matches the structure of the process to be controlled. Position is the integral of speed while speed is proportional to the integral of torque. The 4 quadrant power supply just means that the power converter can handle operation of the motor for all combinations of torque (current) and speed (voltage).

The cascade control structure will operate properly only if the bandwidths of the various regulators have the correct relationship. Bandwidth is the range of frequencies over which the controlled quantity tracks and responds to the command signal. In the cascade control, the current regulator has the highest bandwidth, then the speed regulator, and finally the position regulator has the lowest bandwidth. Therefore, the system is properly adjusted beginning with the innermost current regulator and working outward to the position regulator. The cascade control structure also has the benefit of easily limiting each variable by just limiting the commanded value for that variable.

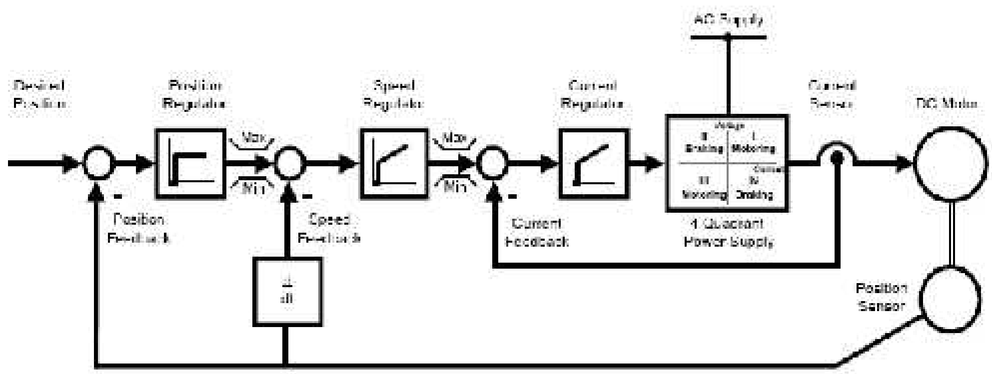



Figure 4.1: Cascade control structure of high performance DC servo system

### 4.2.2 Torque production with a DC servo motor

Understanding the principle of torque production with a dc servo motor (brush-type servo motor) is an excellent foundation for the later discussion of torque production with an ac servo motor (brushless servo motor). Please refer to the representation of a dc servo motor with a mechanical commutator as shown in Figure 4.2.

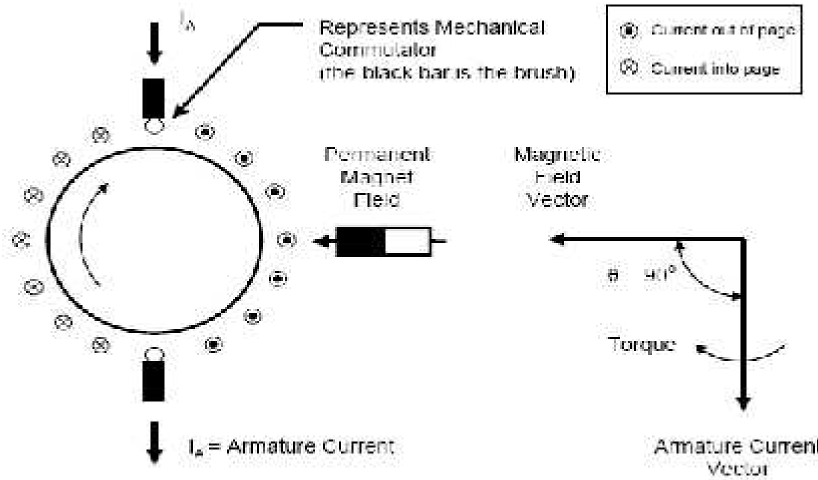



Figure 4.2: DC servo motor principle of operation

The magnetic field created by the permanent magnets is fixed in space and is represented by the vector labeled “Magnetic Field Vector”. A torque is produced by the interaction of the magnetic field and the current-carrying conductors. The torque is a maximum value when the magnetic field vector is perpendicular to the “Armature Current Vector”. The magnitude of the torque is described by the equation:

Torque = $K\,B\,I_A \sin\theta$……………………….………………………………. (4.1)

Where:

K is a constant determined by the specific motor design.

B is the magnetic flux density.

$I_A$ is the armature current.

θ is the angle between the two vectors (the torque angle).

The motor torque produced by the interaction of the current-carrying conductors in the magnetic field will cause rotation of the rotor until the torque angle is zero degrees and further motion would not be possible. The dc servo motor eliminates this condition by using a mechanical commutator on the rotor. The commutator causes the current in each conductor to be progressively reversed as the conductor connected to a commutator bar passes beneath the brushes. The physical location of the brushes in a dc servo motor is such that the torque angle is 90 degrees for both directions of rotation. The result is torque generation that is proportional to armature current.

The classic equations that describe the dc servo motor are as follows:

Torque = KT IA……………………………………………..…………………….... (4.2)

EG = BEMF Voltage = KE nM……………………………………..…………. (4.3)

Where:

KT is the torque constant.

KE is the voltage constant.

BEMF is back electro-motive force.

nM is the motor speed.

The speed voltage EG is created by the armature conductors moving through the constant magnetic field. EG is referred to as BEMF (back electro-motive force) or CEMF (counter electromotive force) because the polarity is such that it will produce armature current that will interact with the magnetic field in such a way as to oppose motion.

The complete block diagram for the dc servo motor including the armature resistance and inductance is shown below in Figure 4.3. Now we can see how the torque of a dc servo motor can be easily adjusted by accurately and rapidly controlling the armature current.

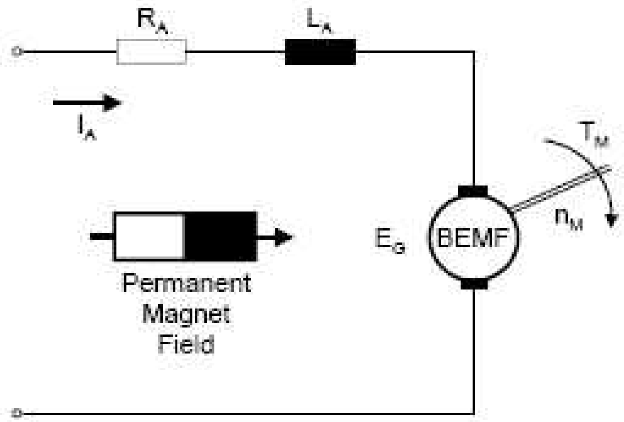



Figure 4.3: DC servo motor block diagram

Where:

$R_A$ = armature resistance.

$L_A$ = armature inductance.

$n_M$ = motor speed.

$T_M$ = motor torque.

$J_M$ = motor moment of inertia.

Unfortunately, while the control of torque with the dc servo motor is very straightforward, the mechanical commutator introduces many limitations. Some of these limitations include:

♦ Periodic maintenance due to brush wear and brush replacement

♦ RFI (radio frequency interference) caused by brush arcing

♦ Voltage (speed) and current (torque) limits caused by the mechanical commutation process
♦ Higher rotor inertia due to armature windings and commutator located on the rotor
♦ A poor thermal situation due to I2R losses in the armature windings on the rotor
♦ And the cost of the commutator system, which needs to be very precise.

The ac servo system with an electronic commutator was developed to eliminate the limitations of the dc servo motor’s mechanical commutator.

**4.3 AC servo system**

The permanent magnet dc servo system or brush-type servo has served as the industry workhorse for many decades. While it is straightforward to control torque with a permanent magnet dc servomotor, the mechanical commutator introduces many serious limitations as listed in the previous section. The brushless servo system was developed to eliminate the limitations imposed by the mechanical commutator of a dc servo system.

The first implementation of a brushless servo system used three-phase permanent magnet motors and square-wave or rectangular shaped currents. The back EMF waveform of the brushless motors ranged from sinusoidal to trapezoidal. The basic idea was to emulate the brush-type dc servomotor by electronically “commutating” the current from one pair of motor windings to another. Completing the analogy with a brush-type servo system, the motor-mounted feedback devices for a velocity controlled brushless servo system included a commutation encoder and brushless tachometer. The commutation encoder provided the position signals used to transition the current electronically from one pair of windings to another. The analogy to the dc servo system resulted in names for these early brushless servo systems such as brushless dc servo, ECM (electronically commutated motor), six-step servo, and trapezoidal brushless servo.

With careful design, these early brushless servo systems had good performance and they demonstrated the possibility for replacing the brush-type servomotor with a brushless servomotor. However, the design challenges and extra cost of these early brushless servo systems limited applications to larger power levels and situations where the extra cost could be justified. This early type of brushless servo is rarely used today in high performance servo systems.

Fortunately, the analogy to a dc servo system can also be extended to sinusoidal current excitation of a permanent magnet motor with sinusoidal back EMF. This technology is commonly referred to as “field-oriented” or “vector” control. Compared to the first generation of brushless servo systems with square-wave currents, a brushless servo system with sinusoidal back EMF and sinusoidal current is much more practical to manufacture and inherently has much smoother torque production due to the gradual commutation process. This type of brushless servo system is commonly referred to as an ac servo, PM (permanent magnet) ac servo, or sinusoidal brushless servo.

The field-oriented or vector control can also be extended to ac induction motors. Variable speed drives (VSDs) with this technology are referred to as vector drives. Vector drives can be applied as servo drives but the induction motors do not have the performance of the permanent magnet ac servo motors due to higher inertia and larger size. However, vector drives are adequate for some servo applications (particularly larger power applications where permanent magnet ac servo systems are not readily available).

### 4.3.1 Torque production with an AC servo motor

The best way to understand the principle behind the ac servo system is to develop an analogy to the dc servo system. As discussed earlier, the dc servo motor has a magnetic field that is fixed in space and the mechanical commutator causes the armature current vector to be perpendicular to the field vector at any motor speed or position. The torque produced by the dc servo motor is easily adjusted by controlling the armature current level. As we will soon see, we have an analogous method for controlling the torque of an ac servo motor using vector or field-oriented control.

Let's start with the magnetic field of the ac servo motor. Figure 4.4 shows a simple representation of an ac servo motor with a permanent magnet rotor and three-phase stator where the windings are spaced by 120 degrees. The magnetic field vector established by the permanent magnets is labeled B. Unlike the dc servo motor where the permanent magnets are stationary, the magnets of the ac servo motor move as they are mounted on the rotor. The challenge of the field-oriented control strategy is to generate the three-phase stator currents in such a way as to keep the composite current vector perpendicular to the magnetic field vector at all times.

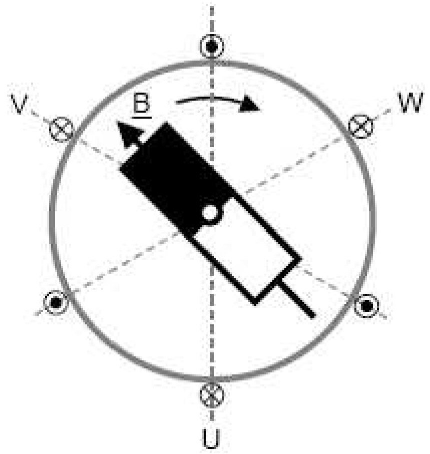



Figure 4.4: AC servo motor with permanent magnet field and three-phase stator

Now let's review the generation of the composite current vector using Figure 4.5. The three-phase stator currents are represented as three sine waves that are displaced in space by 120 degrees with axes labeled as U, V, and W. As examples, the composite current vector is developed for angles of 60 and 90 degrees. Notice for every angle that the composite current vector has a magnitude equal to 1.5IT where IT is the amplitude of the phase currents and 1.5IT has an angular position equal to the angle δ.

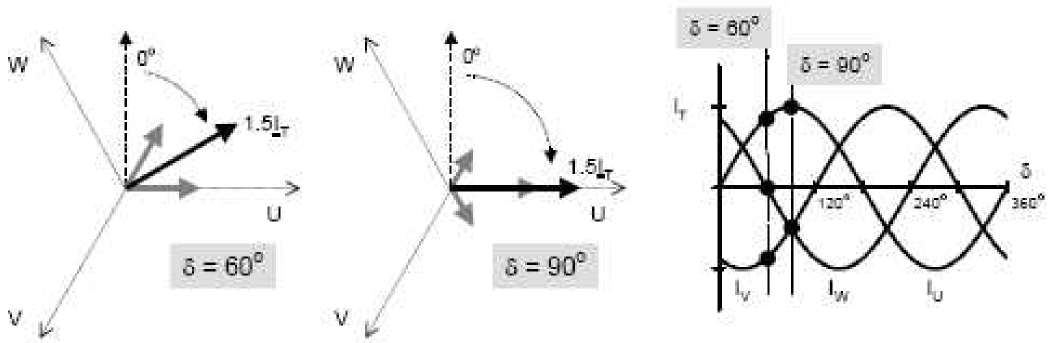



Figure 4.5: Current vector for three-phase AC servo motor

Let's stop and review. We have a fixed amplitude magnetic field vector created by the permanent magnets that rotates synchronously with the rotor of the motor. We also have a composite current vector that rotates at the angular frequency of the phase currents and has amplitude that is proportional to the peak value of the sinusoidal phase currents. Maybe you can see that we have our answer on how to simply control the torque of the ac servo motor.

Let the angle of the motor rotor be called δ and let δ be the angular frequency of the sinusoidal phase currents. Then, we just establish δ = 00 so that the current vector is perpendicular to the magnetic field vector. In practice, this is accomplished by physically orienting the rotor position sensor (usually an encoder or a resolver) so that the composite current vector is perpendicular to the magnetic field vector. Actually, the motor BEMF signal is easier to measure and is uniquely related to the magnetic field vector so the position feedback device is oriented to the BEMF signals during the manufacturing process. In this way, no matter what motion the rotor might make, the current vector will always be perpendicular to the magnetic field vector. We now have an ac servo system where the torque can be controlled just like the dc servo system and where the ac servo motor "looks" just like the dc servo motor to the speed and position regulators. Let's draw a picture of the vector control for an AC servo motor as shown in Figure 4.6.

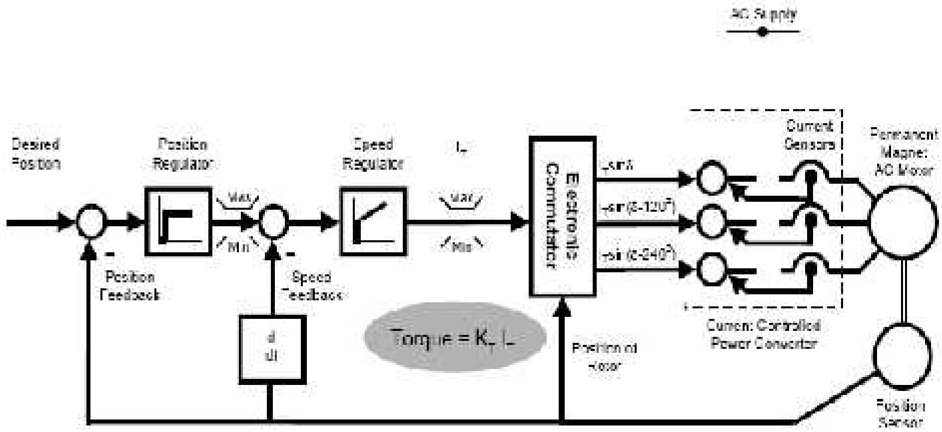



Figure 4.6: Cascade control structure of the high performance AC servo system with field-oriented control

### 4.3.2 AC servo system modes of operation

The digital ac servo system is typically available with six modes of operation:

1. Torque Control Mode

Analog input is the current command signal, which we know from earlier discussions, is proportional to motor torque. No tuning is required but some adjustment may be required to scale the analog input to current or torque.

2. Velocity Control Mode

Analog input is the velocity command. The velocity regulator is tuned for the motor and load.

3. Position Control Mode

Step and Direction (stepper emulation) is the position command. Both the velocity regulator and the position regulator must be adjusted for a specific motor and load.

4. Velocity-Torque mode:

This mode is used when the process require velocity and torque control.

5. Velocity-Position mode:

This mode is used when the process require velocity and position control.

6. Position-Torque mode:

This mode is used when the process require position and torque control.

**4.3.3 Block diagram of AC servo system**

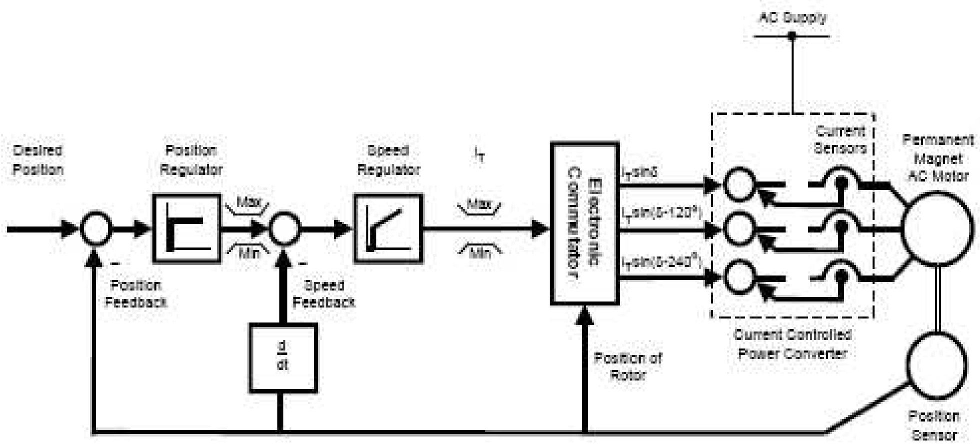



Figure 4.7: Block diagram of AC servo system

## 1. The AC servomotor

The permanent magnet ac servomotor has a very straightforward and rugged construction.

The stator has three symmetrical windings, which are internally connected in a wye configuration. The neutral connection is not brought outside the motor so only three power wires are available from the motor. Compared to the dc servomotor, the construction of the ac servomotor is thermally more effective because almost all of the losses are in the stator where they can be more easily routed to the outside ambient.

The rotor contains the permanent magnets, which can be mounted in different ways depending on a specific supplier's technology. The permanent magnet material ranges from low cost ceramic (ferrite) to the more expensive rare-earth materials such as samarium cobalt or neodymium iron boron ("neo"). Most recent ac servo motor designs use "neo" as a good compromise between magnetic properties, availability, and cost. The rotor also includes a rotary position sensor. The multi-purpose position sensor is used for commutation (or generation of the sinusoidal current commands), velocity feedback, and position feedback.

The equivalent circuit of an ac servomotor is shown in Figure 4.8. This figure is very useful in developing an understanding of the relationship between voltage and current in the ac servomotor.

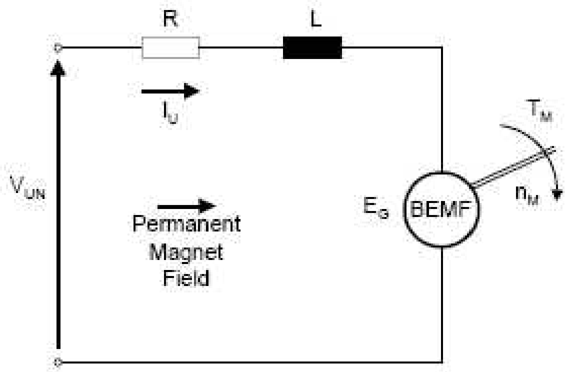


Figure 4.8: Per phase equivalent circuit of an AC servo motor

R: per phase resistance.

(Phase-to-phase resistance = 2 R).

L: per phase inductance.

(Phase-to-phase inductance = √3 L).

VUV: Phase-to-Phase Voltage = √3 VUN.

nM: motor speed.

TM: motor torque.

JM: motor moment of inertia.

EG back emf voltage (line to neutral).

$EG = n_M * Ke\varphi$ ……………………………………………. ……………….. (4.4)

The vector control of the ac servomotor allows the phase current to be kept in phase with the BEMF at all times and by controlling the amplitude of the phase current we can adjust the level of motor torque. The voltage relationships and torque-speed curve for an ac servo system are shown in Figure 4.9 as developed from the ac servo motor equivalent circuit in Figure 4.8.

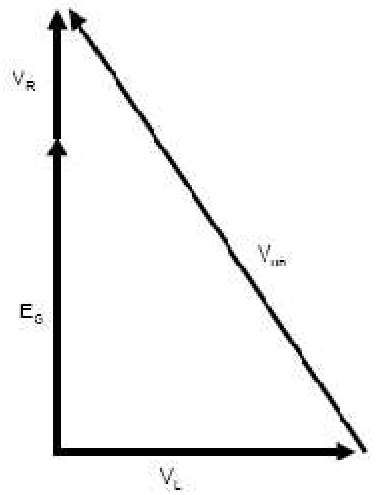



Figure 4.9: Voltage relationships

Vun: required phase to neutral terminal voltage to establish the desired phase current.

VL: voltage across the phase inductance.

VR: voltage across the phase resistance

VL = 2π f L IU………………………………………………….……..……….. (4.5)

VR = IU R ……………………………………………………………….….. (4.6)

Figure 4.10 show the speed-torque curve for AC servo system.

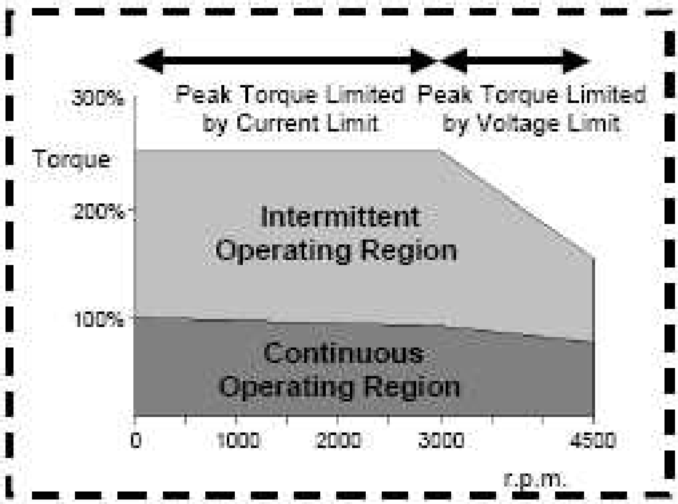



Figure 4.10: Torque-Speed curve for AC servo system

The voltage and current relationships are important because they determine the torque-speed operating boundary for the ac servo system. With vector control, the torque is adjusted by the level of phase current and by keeping the phase current in phase with the BEMF. The terminal voltage required to create the necessary phase current can be determined as shown in Figure 4.9.

The current controlled power converter has a maximum available voltage as determined by the ac supply. When the maximum available terminal voltage has been reached due to requested torque (current) or speed, then the phase current can no longer be properly controlled and we no longer have the proper relationship between torque and current.

The following equations can be used to calculate the ideal maximum voltage available from the power converter. The actual voltage will be lower due to various voltage drops in the system.

$V_{BUS} = \sqrt{2}\, V_{AC}$ ………………………………………………………………… (4.7)

Where:

VAC: AC Supply Voltage.
VBUS: DC Bus Voltage
Maximum VUN = VBUS ÷ ($\sqrt{3}\,\sqrt{2}$) …………………………………….……….. (4.8)

Where:

Maximum VUN: Maximum available line to neutral volts

## 2. The position sensor

The ac servomotor has a rotary position sensor, which is mounted on the non-drive end of the motor. As we have seen in Figure 4.7, the position sensor is used for the electronic commutation of current, speed feedback, and position feedback. The most common position sensor used with ac servomotors is the optical incremental encoder. In special cases, where homing the load on power-up is not acceptable, a more costly multi-turn absolute position feedback device is used instead of the incremental encoder.

Today’s ac servo systems are almost all digital optical incremental encoders, which provide digital information is easily interfaced to digital servo, drives where they offer high resolution and accuracy at an attractive cost. The basic operation of a “wire saving” incremental encoder is shown in Figure 4.11. The low-resolution absolute position start-up signals are only necessary during power-up to initialize the rotor angle inside the digital servo drive. The high-resolution data tracks and marker pulse (C signal) are used after power-up and during normal operation of the system. By using the “wire-saving” design, the same 6 wires can be used for both start-up and normal operation, which minimizes the cost and diameter of the cable running between the drive and motor. Including the dc supply wires, the “wire-saving” encoder only requires 8 total wires. However, in practice, small gauge wire is used so it is common to double or even triple-up on the supply lines in order to minimize voltage drop over longer cable lengths. As an alternative, some drives use a pair of voltage sensing lines to measure supply voltage at the encoder and then adjust the supply voltage at the drive to maintain the proper voltage at the encoder.

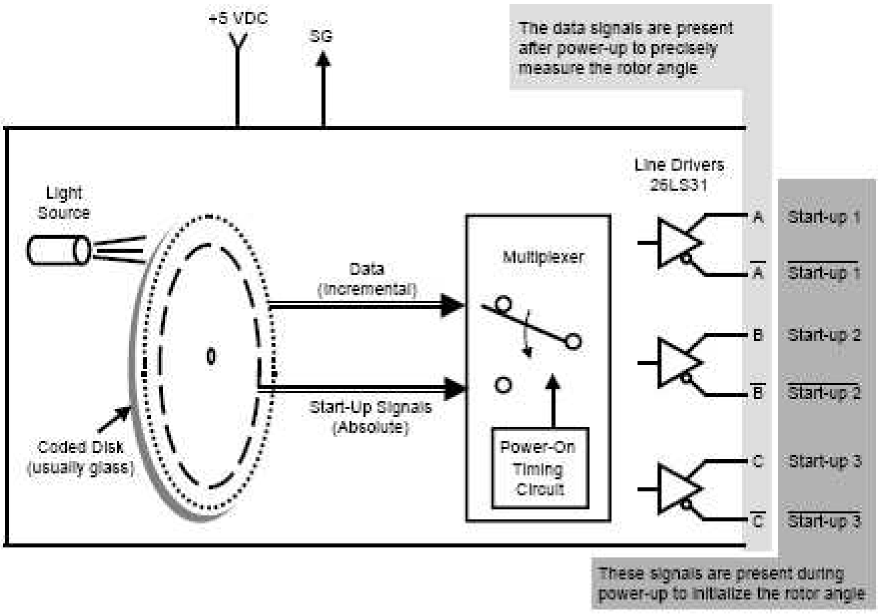



Figure 4.11: Principle of operation for a "Wire-Saving" incremental optical encoder

A representation of the signals from the incremental optical encoder is shown in Figure 4.12. For simplicity, the signals are shown without the complement signals from the line drivers. However, in practice, differential feedback signals are essential to eliminate noise problems and to facilitate long cable lengths.

The encoder is attached to the ac servomotor in a very particular and precise way during the assembly of the motor. From earlier discussions, the rotor angle must be defined so that the composite current vector is kept perpendicular to the magnetic field at all times. The start-up signals provide low-resolution absolute position information to initialize the rotor angle in the servo drive. The resolution of the start-up signals provide for ± 30 degree accuracy of the torque angle.

As torque is proportional to the sine of the torque angle, we have at least 86% of maximum torque available to move the load up to one mechanical revolution until we pick-up the C signal or marker pulse. After we detect the marker pulse, the torque angle is set to the exact value necessary for a 90-degree torque angle.

The marker pulse has a unique position relative to the start-up signals which is determined by the manufacture of the encoder and which is specified by the supplier of the servo system. The marker pulse also has a unique relationship to the motor BEMF signal and is precisely aligned during the installation of the encoder onto the motor. The accuracy of the marker pulse to the motor BEMF signal is usually at least ± 2 mechanical degrees, which provides more than 99% of maximum torque for 4, 6, and 8 pole motors.

Finally, the A and B data signals typically provide 2000 cycles per mechanical revolution. The servo drive encoder interface circuit is designed to detect all of the edge transitions for the data signals so the 2000 "line" encoder provides 8000 counts or pulses per revolution (ppr).

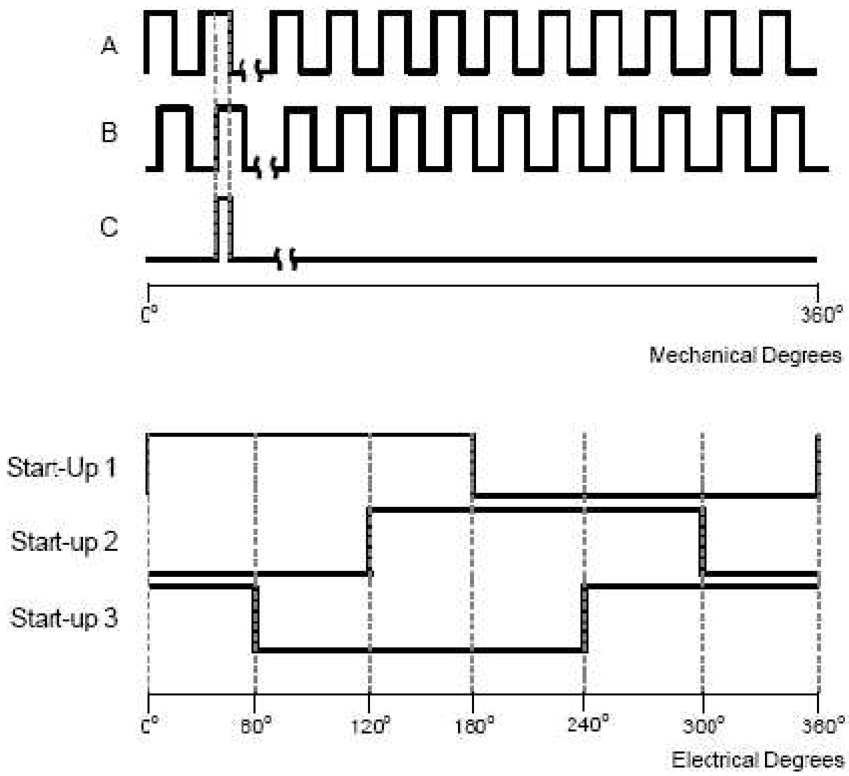



Figure 4.12: Representation of the incremental encoder signals

Electrical Degrees = (Mechanical Degrees) (Pole Pairs)
(Example: a 4 pole motor has 2 pole pairs)

### 3. The current controlled power converter

As discussed earlier, the ac servo motor produces torque, which is proportional to the amplitude of the composite current vector. As you can imagine, the ac servo drive must produce current accurately and with high response. This extremely important task is the work of the current controlled power converter as shown in Figure 4.13.

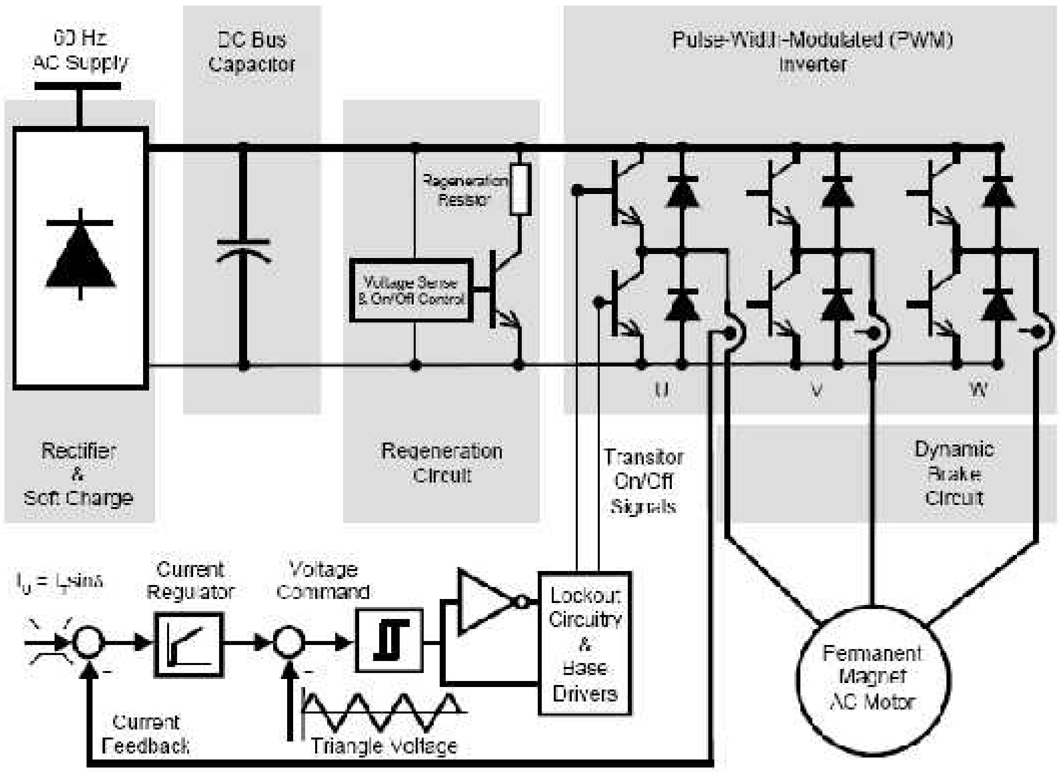



Figure 4.13: Block diagram of the current controlled power converter

The system is supplied by the ac mains, which typically is required to be single phase or three phase voltage at 230 Vrms (+10%/-15%) and 60 Hz (± 3%). Sometimes the ac supply is buffered by a transformer in order to provide the correct voltage level. The primary attribute of the ac supply is that it needs to maintain the required voltage level even as it is loaded by the servo drive(s) or other items attached to the supply.

The diode rectifier converts the ac input into a dc voltage, which is called the “dc bus”. Included with the diode rectifier is a circuit to control the inrush current(s) during power-up. Without the “soft start” or “soft charge” circuit there would be very large inrush currents to charge the dc bus capacitor. After initial power-up, the rectifier circuit is free to provide the necessary energy to the servo system as required.

The dc bus capacitor has a large value, which serves two purposes. One purpose is to act as a large filter so that a smooth dc bus voltage is available to the inverter. The second purpose is to help absorb energy during regeneration or braking of the motor and load. While the diode rectifier can supply power during motoring or driving, it cannot return power to the ac supply during braking. The regeneration energy is absorbed by the dc bus capacitor until it charges to a maximum allowable voltage and then the regeneration circuit “dumps” excess energy in the regeneration resistor where it is eliminated in the form of heat. Most ac servo drives include a small built-in regeneration resistor while having the provision for adding an external resistor with a much larger wattage.

The inverter is designed with power switches that are turned “on” or “off”. These power switches can be bipolar transistors or power FETs but most ac servo drives today use a newer switch referred to as an IGBT (insulated-gate bipolar transistor). The IGBT combines the rugged output of the bipolar transistor with the gate drive and fast turn-off time of the power FET. The inverter topology, with the six switches and the “flyback” diodes, provides four quadrant operation of the ac servo motor by allowing energy to flow to and from the motor.

Let’s take a look at the current controller design for one of the three phases. The other two phases operate in an identical fashion.

The desired current or current command is IU and it can be limited to a user defined value (up to a maximum as determined by design limits). The current command is compared to the current feedback to produce a current error. As you can imagine, the current sensors must be very accurate and responsive devices, as they must absolutely produce a faithful reproduction of actual current.

The current error is processed by the current regulator to produce the voltage command. The current regulator has a high-gain to minimize the current error over the operating range of the system. The voltage command is compared to a triangle voltage to generate the PWM (pulse width- modulated) signals that command the power switches to turn-on and turn-off. The switching frequency of the PWM inverter is usually in the range of 5 to 20 kHz in order to support the high current loop bandwidth and to minimize the audible noise and level of current ripple. The –3dB bandwidth of the current loop is usually well over 1,000 Hertz.

The power switches are not perfect and they do take some time (typically a few μsecs) to turnoff after receiving the command to turn-off. Unfortunately, the switches respond to the turn-on signal more rapidly so the “on” and “off” commands are processed by some special circuitry to prevent the upper and lower switches from simultaneously conducting current. Such a condition is referred to as a “shoot-through” and it is as bad as it sounds. The “lock-out” circuitry introduces a small delay in the turn-on signal to prevent shoot-through conditions.

Now for the best news of all the current controller is the domain of the ac servo system manufacturer and requires no user adjustment at all! The operation of the current controller is absolutely critical to the performance of the servo system and the necessary adjustments only involve knowledge of the servo drive design and the motor design. Therefore, the servo system manufacturer has all the information necessary to provide for the optimum set-up with a minimum of user intervention. At most, the user will be asked to supply the drive with the motor model number or similar identifier.

Finally, a dynamic brake (DB) circuit is shown between the inverter and the ac servo motor. The DB is used in the event of a servo drive fault condition to help brake the motor. Often, the DB circuit is included inside the servo drive, which is very convenient. The DB circuit uses contactors to disconnect the motor from the inverter and to connect the motor windings together through resistors. If the motor is rotating, the BEMF causes current to flow in such a way as to retard rotation or to dynamically brake the motor.

**4. The velocity regulator**

Let's begin with a block diagram of the velocity controlled servo system as shown in Figure 4.14. The most common choice for the velocity regulator is a PI controller (proportional plus integral controller). The proportional gain (Kvp) and the integral gain (Kvi) are adjusted to achieve the desired response. The well-damped current controller can be approximated at the lower frequencies as a first order lag. Recall from the previous section that the current controller is set-up by the servo system supplier and no adjustments are required by the user. The load and motor are modeled as a pure inertia but can be complicated as required to model any actual load. Also, notice that the velocity controller has two inputs to consider: the speed command and the often overlooked load or disturbance torque.

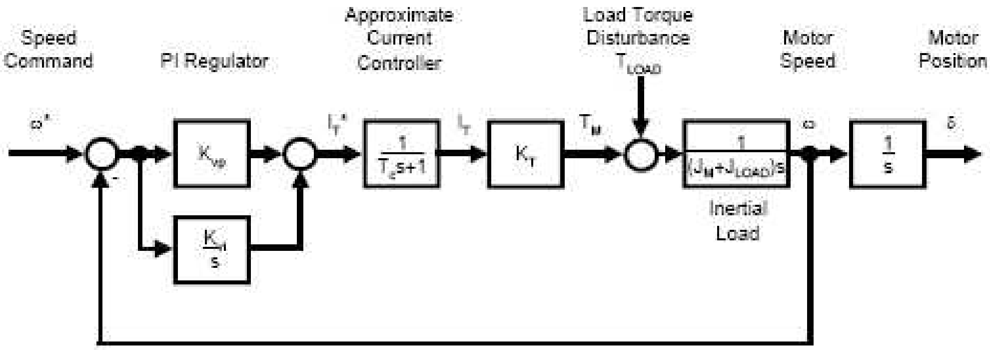



Figure 4.14: Block diagram of the velocity regulator

The Kvp term is increased to achieve faster response but unfortunately also has the effect of simultaneously slowing down the response of the integrator. The Kvi term is raised to increase the response of the integrator (reduce the integrator time constant). This unfortunate interaction is better seen by rearranging the block diagram of the PI regulator into a form equal to Kvp (1 + 1/Tvis) where the integrator time constant is Tvi = Kvp/Kvi. The interaction of Kvp and Tvi makes it difficult to intuitively tune the PI controller. Fortunately, the digital ac servo drive is able to perform the math so that the proportional gain and the integrator time constant can be independently adjusted without the interaction. Figure 4.15 shows the revised block diagram of the velocity regulator with independent adjustment of gain and integrator time constant where we have also assumed perfect current control for additional simplicity.

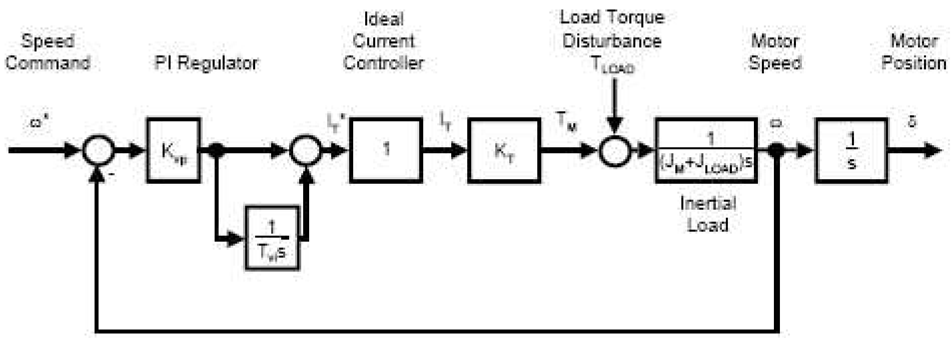



Figure 4.15: Block diagram of PI controller with Kvp and Tvi adjustments

In practice, the velocity regulator is tuned or adjusted to result in a well-behaved control system as defined by stability, steady-state accuracy, and transient response, let's discuss these design objectives in some more detail:

**1. Stability**

The most common method of manually tuning the velocity controller is to observe the speed response to a small-signal step change in the speed command. For best results, this must be done with the motor connected to the actual mechanical load. Small-signal means that the current command is not reaching a limit condition during the tuning process. The desired response is one that reaches the set point with acceptable rise time, overshoot, and settling time. The objective is to find values for Kvp and Tvi that minimize rise time, overshoot, and settling time while still allowing for some safety margin in the stable operation. It is not good practice to tune the system with gain values that leave the system on the verge of instability. Figure 5.16 shows some examples of velocity responses to small-signal step changes in the velocity command as we make various changes to Kvp and Tvi.

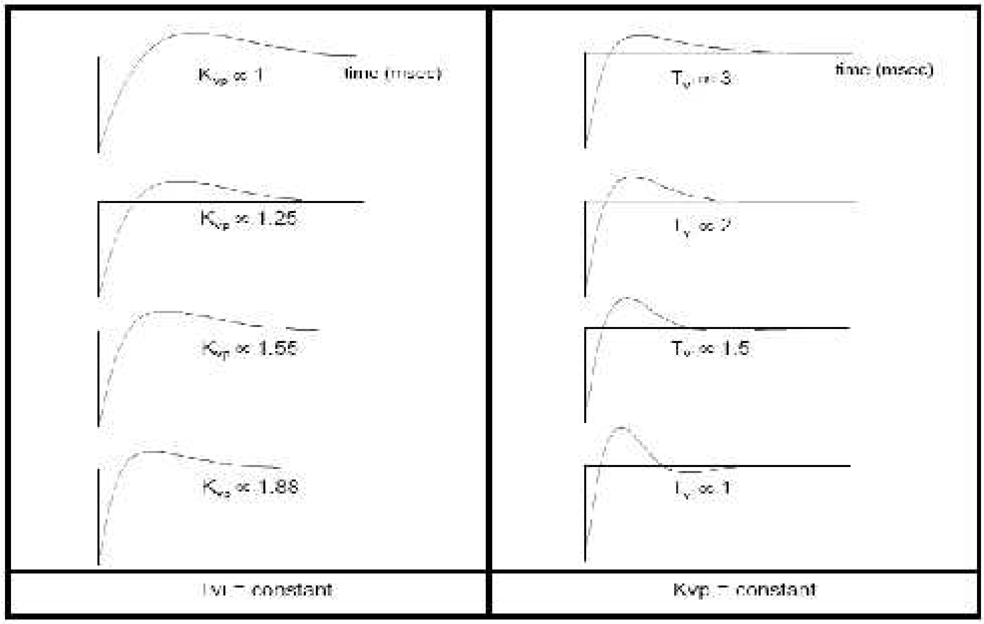



Figure 4.16: Velocity response to small signal step change in velocity command

**2. Steady-State accuracy**

The well-tuned servo system should not have any steady-state error for a step change in the velocity command or load torque. The closed loop transfer functions developed from Figure 4.8 are shown below (where we have also assumed an ideal current controller):

$$\omega / \omega^* = (Kvp / J)(s + Kvi / Kvp) / (s^2 + (Kvp / J)s + Kvi / J) \quad \text{……….……...…(4.9)}$$

$$\omega / T_{LOAD} = (1/J)\, s / (s^2 + (Kvp / J)\, s + Kvi/J) \quad \text{………………………….….… (4.10)}$$

$$\delta / T_{LOAD} = 1/J / (s^2 + (Kvp / J)\, s + Kvi/J) \quad \text{…………………………...…... (4.11)}$$

Using the final value theorem, the steady-state error for step-command inputs can be determined. The first two equations show that the velocity error is zero for a step change in the velocity command or the torque disturbance. However, the last equation shows that there is a steady state position error for a step change in load torque where $\delta/TLOAD = 1/Kvi$. The static position error or “stiffness” of the velocity loop is improved with higher Kvi values or a smaller value integration time constant. Do not be concerned at this time with the static position error as we will show in the next section that when the position loop is closed, the static position error for a step change in load torque will also be zero. So, we can conclude that the PI controller as a velocity regulator provides excellent attributes for steady-state accuracy.

**3. Transient response**

The transient response is analyzed in much the same manner as the relative stability. We are looking for a response to a step change in command or load torque

that has acceptable rise time, overshoot, and settling time characteristics. The closed-loop response of a well-tuned control loop often has characteristics that are dominated by a pair of under damped complex poles. For this case, a useful rule of thumb that relates the rise time and closed loop bandwidth is as follows:
(Rise Time) (Closed Loop Bandwidth in Hertz) = .45**.**

Once again, the objective for the tuning is to provide just enough response and stiffness without leaving the system on the verge of instability as in Figure 4.17. We want a safety margin to allow for any changes in a particular system and to provide standard tuning values that can be reapplied on multiple systems.

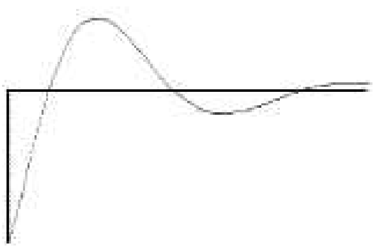


Figure 4.17: Velocity response bordering on instability

**4. The position regulator**

Position control applications fall into two basic categories: contouring and point-to-point.

In general, contouring applications are focused on following a path. Contouring applications require the actual position to follow the commanded position in a very predictable manner and to have high stiffness to reject the effect of any load torque disturbances. Point-to-point applications are not usually concerned with path control but are concerned with move time, settling time, and the velocity profile.

Independent of the positioning application, the basic position controller is shown in Figure 4.18. The velocity controller is modeled as a first order lag where the time constant is determined by the useful bandwidth.

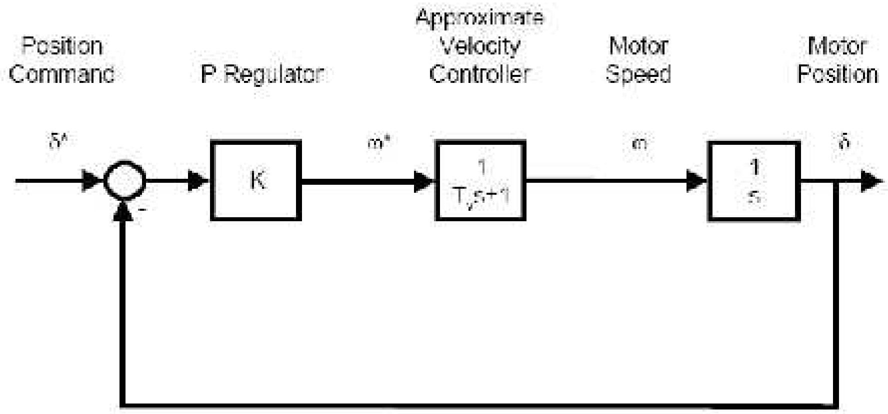



Figure 4.18: Block diagram of the position regulator

Understanding the operation of the position regulator with only proportional gain is a good first step. The gain of the open loop frequency response for the system in Figure 4.18 crosses 0 dB at a value equal to K. Therefore, the bandwidth of the position loop can be expressed as follows:

K = 16.66 rad/sec = 2.65 Hz = 1 meter/min/mm = velocity/position error.

The actual position controller contained within the ac servo drive will have a gain KP that has useful units such as rad/sec. This is very helpful when tuning the position loop.

Now, let’s take a look at the static stiffness of the simple position loop. From Figure 4.18, we can see that the steady-state position will equal the commanded position due to the effect of the velocity integration into position. The effect of a step change in load torque is a little more difficult to analyze. However, referring to

Figure 4.19, we can laboriously develop the transfer function between position and load torque as having the form:

$\theta = (1/J)/ (s2+ (1/J) (GC) (s+KP)) T_{LOAD}$…………………………..…………… (4.12)

If the velocity controller (GC) is a PI controller then we can now demonstrate using the final value theorem that there is no position error in the steady-state condition when there is a step change in load torque. This is another good feature of the PI controller in the velocity loop.

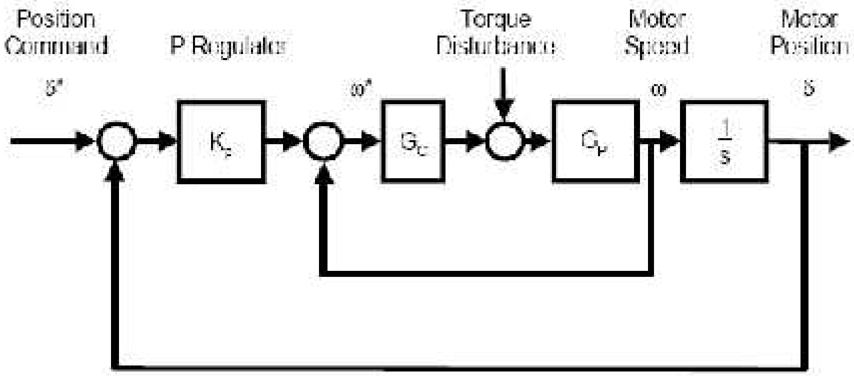



Figure 4.19: Block diagram of position loop with torque disturbance

The actual position regulator can be more complicated than a simple proportional gain. A more general position controller is shown in Figure 4.20.

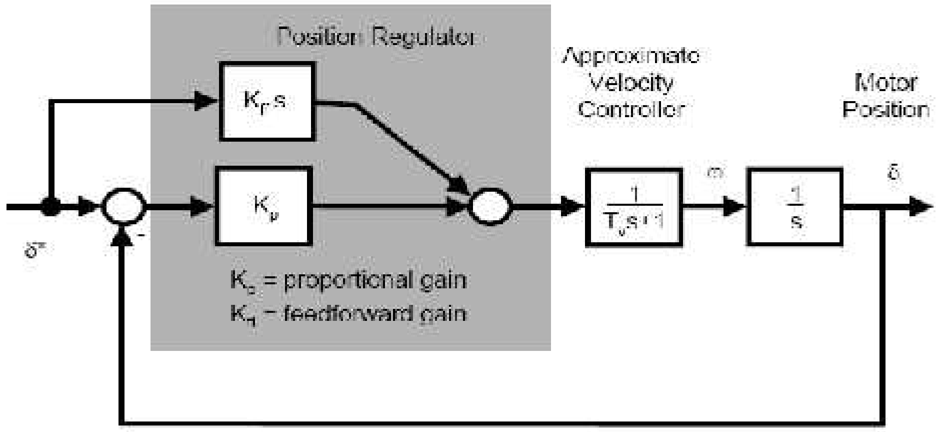



Figure 4.20: General structure of position regulator

Let's quickly review the features of the general position regulator shown in Figure 4.20.

The proportional gain remains the most important term. The proportional gain will generate a velocity command that is proportional to position error. In other words, with only a proportional gain, motion will occur only if there is a position error. In fact, the position error will increase with increasing speed. The dynamic position error or following error can only be reduced by increasing the proportional gain. However, there is a limit on position loop gain (determined by the useful bandwidth of the velocity loop) and if the gain is increased too much then the actual position will begin to overshoot the commanded position which is normally not acceptable. However, recall that the static position error is zero if the position command is not changing.

The feedforward gain is used to reduce the following error. The feedforward gain generates a velocity command signal that is proportional to the derivative of the position command. Ideally, 100% feedforward would generate the exact velocity command without the need for a position error. However, in practice, the system is not ideal and it is prudent to use less than 100% feedforward since too much feedforward will cause the actual position to go farther than the commanded position. In any event, the use of feedforward will significantly reduce the following error even though the proportional gain is at a level for proper stability as shown in Figure 4.21.

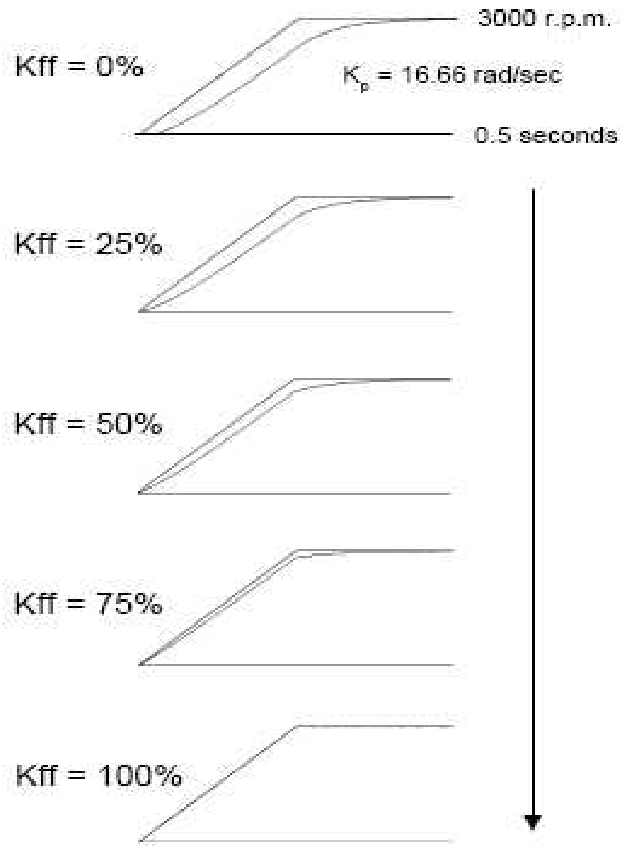



Figure 4.21: Actual velocity for a ramped velocity command and the effect of velocity feedforward on following error

# Chapter 5
# Machine Simulation

## 5.1 Simulation

As we have mentioned in the previous chapters that the automatic wood carving and decorating machine contains four motors: three AC servomotors, and one AC synchronous motor. To make a simulation to these motors and to the machine we would use a computer program called (SIMPLPORER).

The simulation process passed through number of steps:

- Construction of the equivalent circuit of each motor.
- Construction of the control circuit of each motor individually.
- Construction of the control circuit of the machine.

### 5.1.1 The AC servo motor equivalent circuit

To construct the equivalent circuit of the AC servo motor we need the following elements from the (SIMPLPORER) program:

- Voltage sources (1X): Basics\Circuit\Sources\Voltage source.
- Thyristors (4X):Basics\Circuit\Semi conductors System Level\Thyristor.

- Capacitor (1X): Basics\Circuit\Passive Elements\Capacitor.
- Ideal Switch (6X): Basics\Circuit\Ideal Switches\Ideal Switch.

- Diodes (6X): Basics\Circuit\ Semiconductors System Level\Diode.

- PM AC Motor (1X): Basics\Circuit\Electrical Machines\PM Synchronous With Damper.

After collecting these elements we construct the equivalent circuit of the power converter of the AC servomotor as shown in Figure 5.1:

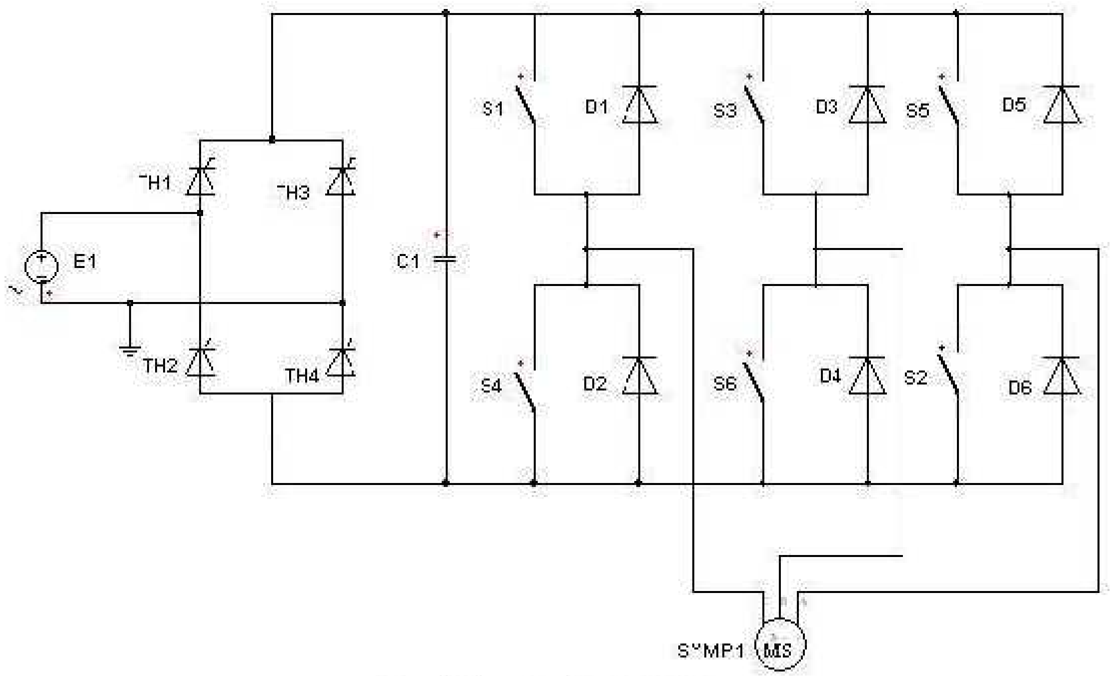



Figure 5.1: The equivalent circuit of AC servo motor

### 5.1.2 The AC servo motor control circuit

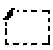
To construct the control circuit to the previous equivalent circuit we need to the following elements from the (SIMPLPORER) program:

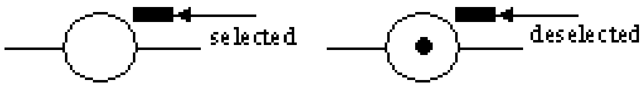
- State (10X): Basics\States\State11.
- Transition (10X): Basics\States\Transition.
- Constant (1X): Basics\Blocks\Sources blocks\Constant value.
- Saw Tooth (2X): Basics\Tools\Time Functions\Saw-Tooth.

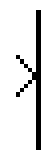
We need tow control circuits one to trigger the thyristors in the controlled rectifier (B6C) which used to control the input DC voltage, and the second to control the 3-PH inverter operation and (the sequence of the switches) to use it to convert the voltage from DC to AC.

Before explaining the control process procedures, we will show the function of each element used in it:

**1. State graphs**

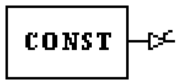
Control process can be realized in SIMPLPORER very fast and easy using State Graphs. This concept is based on analyzing the control task in States with dominant properties. An actual state is designed as active. The process procedure is represented as sequence of states. To specify the action of each stat, double-click on the state and then on the icon  and choose from the list the desired action. At the simulation start, a start state must be defined. Definition of start stat is achieved by clicking on the square area as shown in the following Figure:




In the Transition  , the conditions for the switching from one state to the next are defined. The switching from one state to the other will follow if the transition has the logic value “true”.

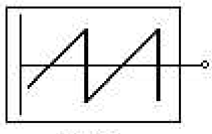
**2. The constant**

It’s a block where the firing angle will be later saved.




**3. Saw-Tooth**

It is a function which will be used as a help function for comparing the firing angle with the value of it.




**4.The control circuit of the inverter**

The control circuit of the inverter is shown in Figure 5.2:

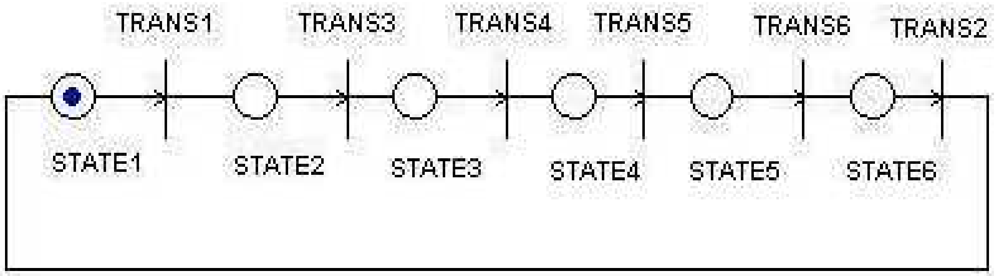


Figure 5.2: The control circuit of the inverter

The states and the transitions in the Figure used to control the states of the switches in the AC servomotor equivalent circuit to satisfy the inversion. The control process must consider the graphs of Figure 5.3, which show when the switch is ON or OFF.

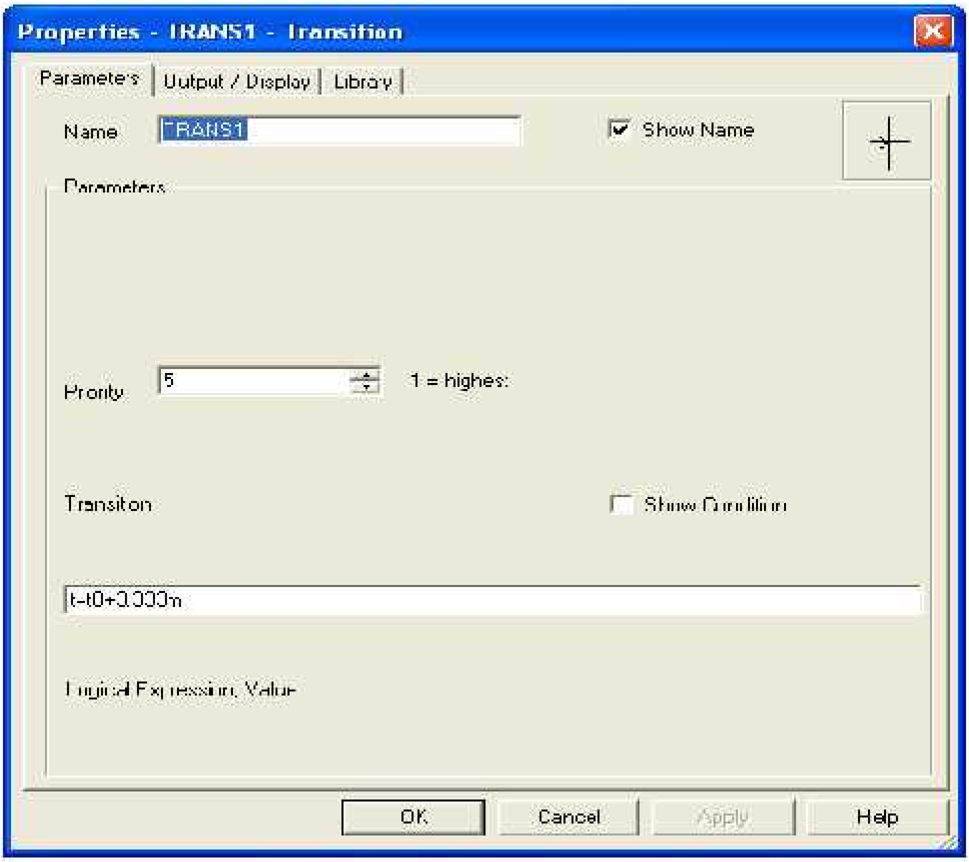
From the Figure5.3, we noted that at every (60º) the switches a case is changing, that is three switches are turned on, and the other three switches are turned off.

Figure 5.3: Inverter switches timing diagram

The control process is done as the following:

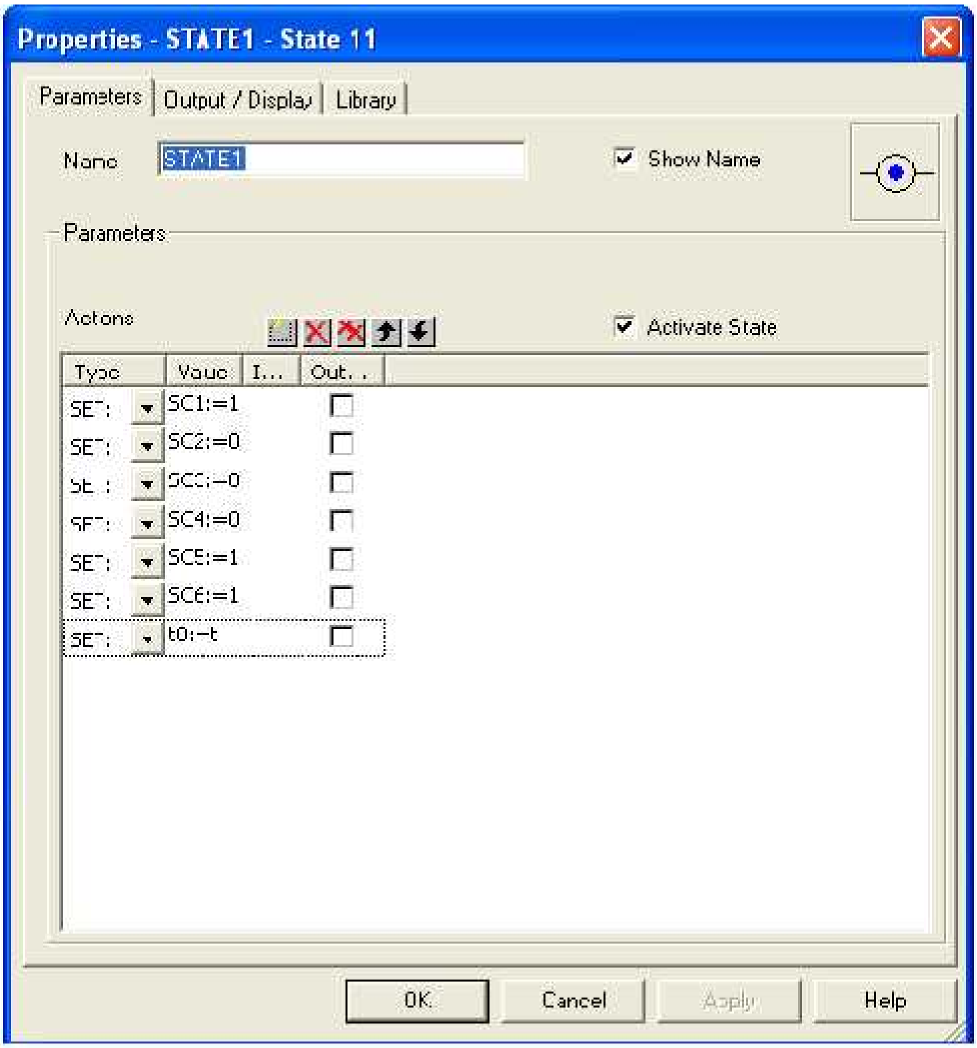
- Named the control signal of each switch by double click on the switch and choose a suitable name to its control signal, for example control signal of switch (S1) is (SC1).
- Determine the start state as we have mentioned.
- Determine the period of switches signal according to the voltage source frequency, to determine the time at ($60^o$).
- Double-click on the transition and determine the time which you would like the case of the state is transferred to the next after it (here the time that matching $60^o$).

The following Figure shows that for (Transition 1):



- Each state works after (3.333ms) from the previous state.
- The time at (60º) equal here to 3.333ms as the input source period equal to 20ms (F=50Hz).
- Double-click on each state and determine which switch is ON or OFF according to the Figure 5.3 .

For example, in the first 60º, S1, S5, and S6 are switched ON, and S2, S3, and S4 switched OFF, as shown in figure 5.3, this could be done in the SIMPLPORER as the following Figure for State 1:



- (SET: t0:= t) to load the first state with the time in the finish step (after the period is ended) to repeat the process, which makes the output, signal periodic.

✓ The control circuits of the controlled rectifier (B6C) are shown in Figure 5.4 and Figure 5.5.

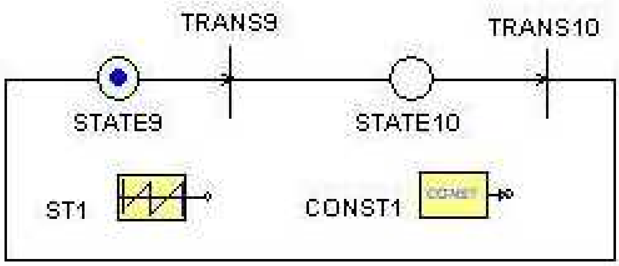



Figure 5.4: Control circuit for triggering the firing angles of TH1 and TH4

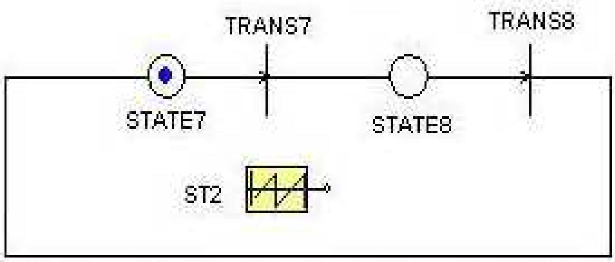



Figure 5.5: Control circuit for triggering the firing angles of TH2 and TH3

The first circuit used to trigger the firing angles of the thyristors TH1 and TH4 as these tow thyristors are working at the same time( in the positive half wave of the voltage source).

The second circuit used to trigger the firing angles of the thyristors TH2 and TH3, as they are working at the same time (in the negative half wave)

- The frequency and period of ST1 must be identical with the frequency and period of the voltage source (here F=50Hz and T = 20).
- The phase of ST1 must be synchronized to the phase of the voltage at the terminals of TH1 and TH4 (the positive half wave of the source).
- The amplitude of ST1 must be equal to (180 V).

Figure 5.6 shows the form of ST1:

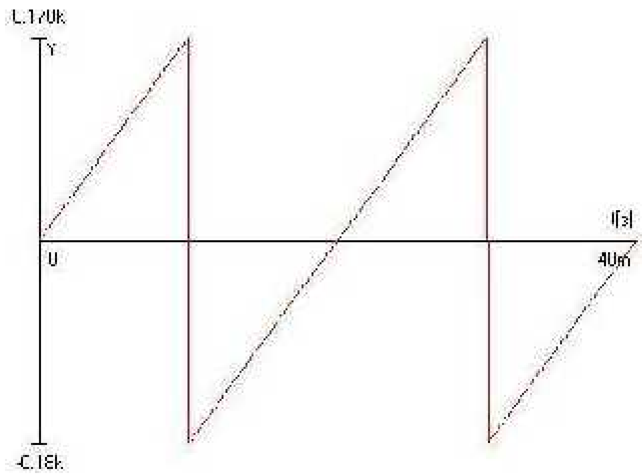


Figure 5.6: The form of ST1

- The frequency and period of ST1 must be identical with the frequency and period of the voltage source (here F=50Hz and T = 20).
- The phase of ST2 must be synchronized to the phase of the voltage at the terminals of TH2 and TH3 (the negative half wave of the source).
- The amplitude of ST2 must be equal to (180 V).

Figure 5.7 shows the form of ST2:

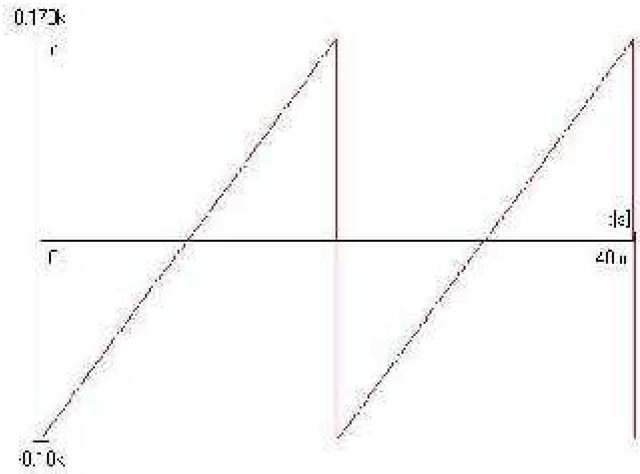


Figure 5.7: The form of ST2

- Now name the control signal of each thyristor, (the control signal name of TH1 and TH4 must be identical and the control signal name of TH2 and TH3 must be identical too).
- In Transition 9 write (ST1.VAL>=CONST1.VAL).
- In Transition 10 write (TH1.I=0).
- In Transition 7 write (ST2.VAL>=CONST1.VAL).
- In Transition 8 write (TH2.I=0).
- Choose the value of firing angle of the thyristors by double-click on the CONST block.
- In State 9 set the value of the control signal of the TH1 and TH4 to (0) to switch off them as the pervious transition of it say that their holding current is equal to zero(TH1.I=0).
- In State 10 set the value of the control signal of the TH1 and TH4 to (1) to switch on them, as the pervious transition of it say that the firing angle of them it reached (ST1.VAL>=CONST1.VAL).
- Do the same thing to the other two thyristors.

From the previous control circuits we can control the speed of the AC servomotor.

Figure 5.8 and Figure 5.9 show the curves of the speed and the torque of AC servo motor at 50Hz frequency and 20º firing angle:

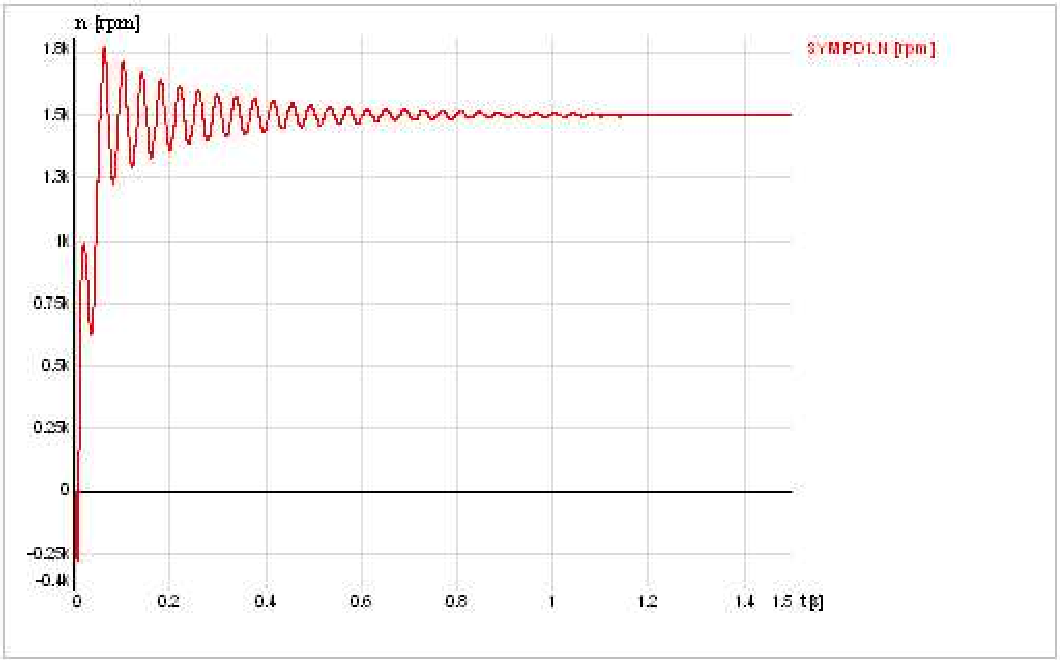



Figure 5.8: The AC servo motor speed curve

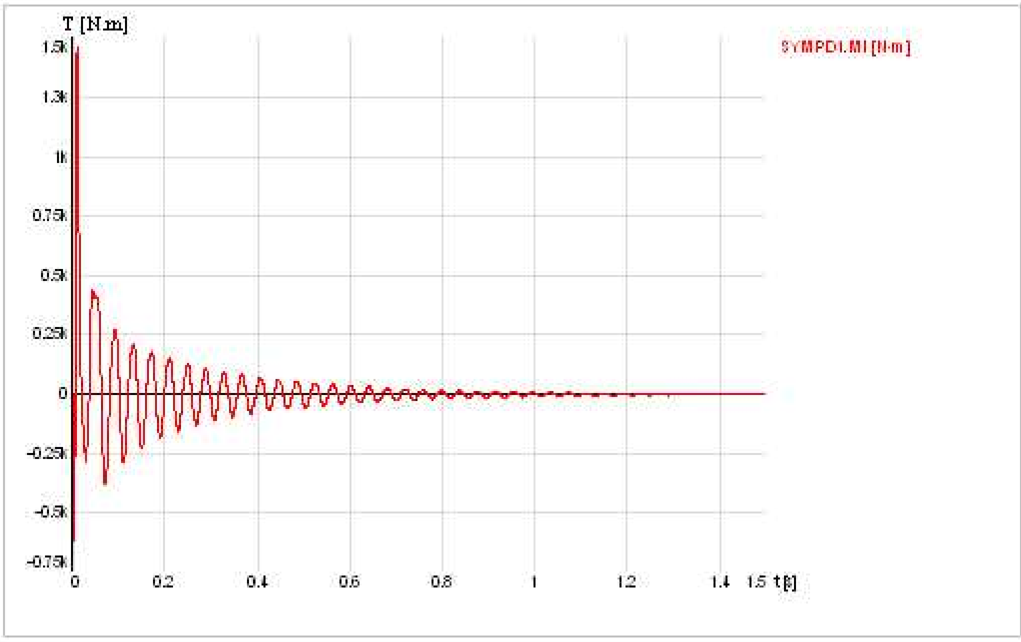



Figure 5.9: The AC servo motor torque curve

**Machine control circuit**

Movement of the machine motors takes the following arrangement to satisfy the machine operation:

1. The synchronous motor works firstly, after the machine is switched on.
2. The Z-axis motor works secondly.
3. The X-axis and Y-axis motors work in determined strategist to applied the shape which come from the computer on the wood, for example if there is an arc in the shape, x-axis and y-axis motors must work at the same time.

We used the (SIMPLPORER) program to simulate the sequence of the motor operations, by take the various probabilities that the motors are operated.

The machine control circuit based on the following sequence:

- Operating the synchronous motor firstly.
- Operating the z-axis motor after 20ms after the synchronous.
- Operating the x-axes motor after 20ms after the z-axis.
- Switching off the x-axis and operate the y-axis motor after 20ms.
- Operating the x-axis and y-axis motors after 20ms.

The machine control circuit is shown Figure 5.10:

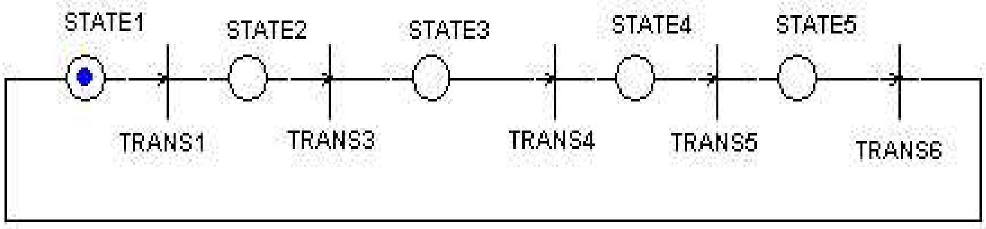



Figure5.10: Machine control circuit

Figure 5.11 to Figure5.14 show the speed of the motors based on the previous control circuit:

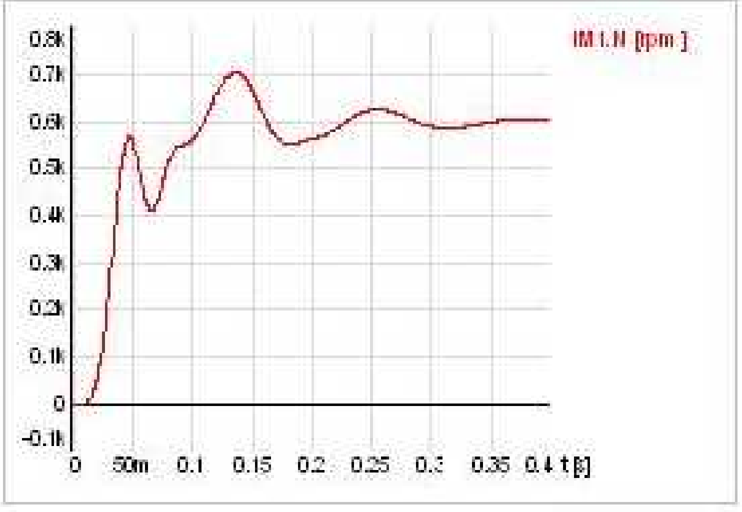



Figure 5.11: The AC synchronous motor speed curve

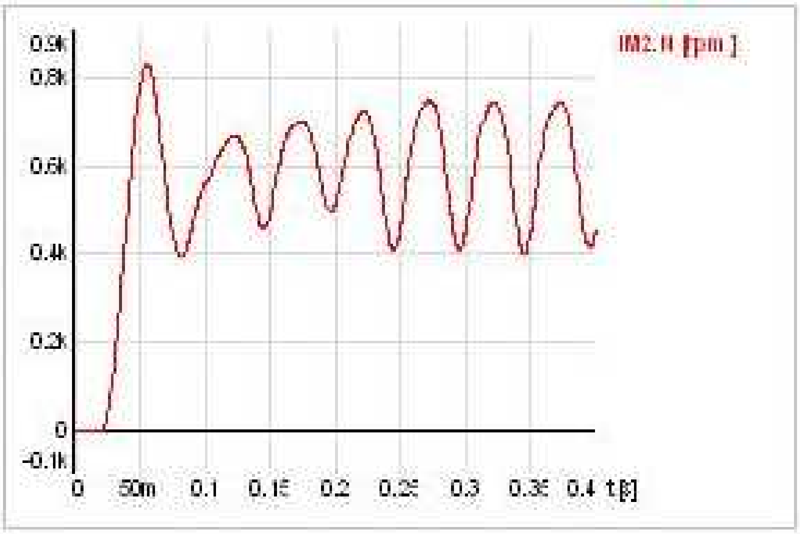



Figure 5.12: The AC Z-servo motor speed curve

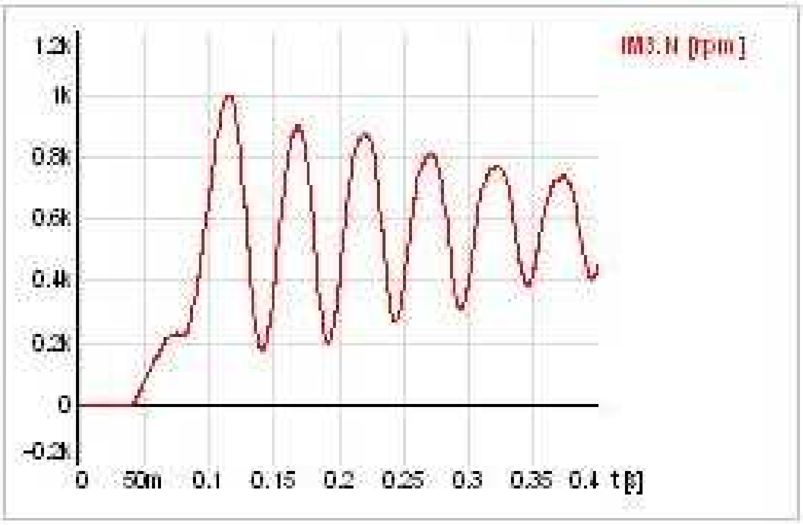



Figure 5.13: The AC X-servo motor speed curve

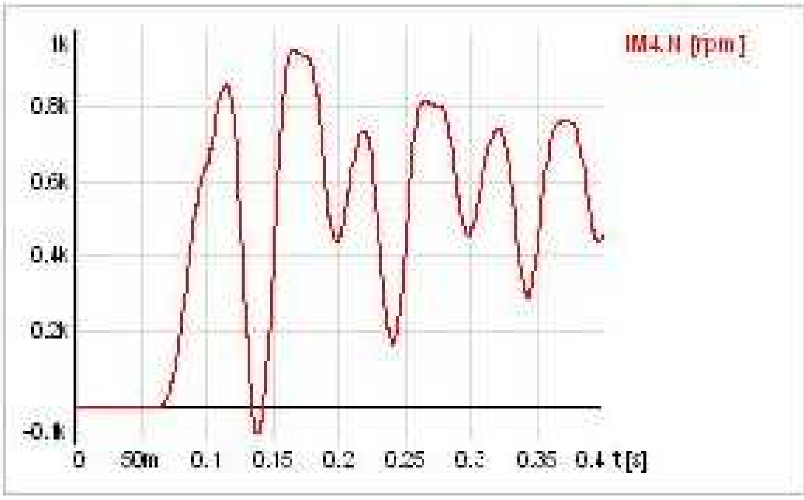


Figure 5.14: The AC Y-servo motor speed curve

# Chapter Six
# Machine Design

## 6.1 Body of the machine

Figure 6.1 describes the body of the automatic carving and decoration machine; we can divide this body into four major parts: three sliding bridges, and the base of the machine which contain the work plane. One of the sliding bridges is (250CM) length and (30CM) width and (20 CM) height, this sliding bridge moving in the Y-direction, the second sliding bridge is (45CM) length and (45CM) width and mounted on the Y-sliding bridge but moving in the X-direction, the third sliding bridge is ( 20 CM) length and (20 CM) width and moving in the Z-direction, the base of the machine is (90 CM) height and (250 CM length) and (200 CM) width.

The work plane of the machine contain a four plates, each plate is (122 CM) length and (97 CM) and weight (75 Kg), there a (6 CM) space between these plates, in this space we put the clamp (vise) which is use to fix the wood board on its position to become ready to carving and decoration operations.

The body contains four motors, three AC servo motors (X, Y, and Z) and one AC synchronous motor, three racks and pinions, and six linear bearings. The three AC servo motors are employed the pinions and the racks to tangentially drive the load in the X, Y and Z directions. The linear bearing used to reduce the friction and to make the equilibrium in the bridges and its load.

The Y- motor used to move the first sliding bridge and its load in the Y-direction and it is mounted on the base of the machine, the X- motor used to move the second sliding bridge and it load in the X- direction and its mounted on the first sliding bridge of the machine, the Z- motors used to move the third sliding bridge and its load in the Z- direction and its mounted on the second sliding bridge of the machine, the AC synchronous motor used to rotate the cutting part carving part and its mounted on the third sliding bridge of the machine.

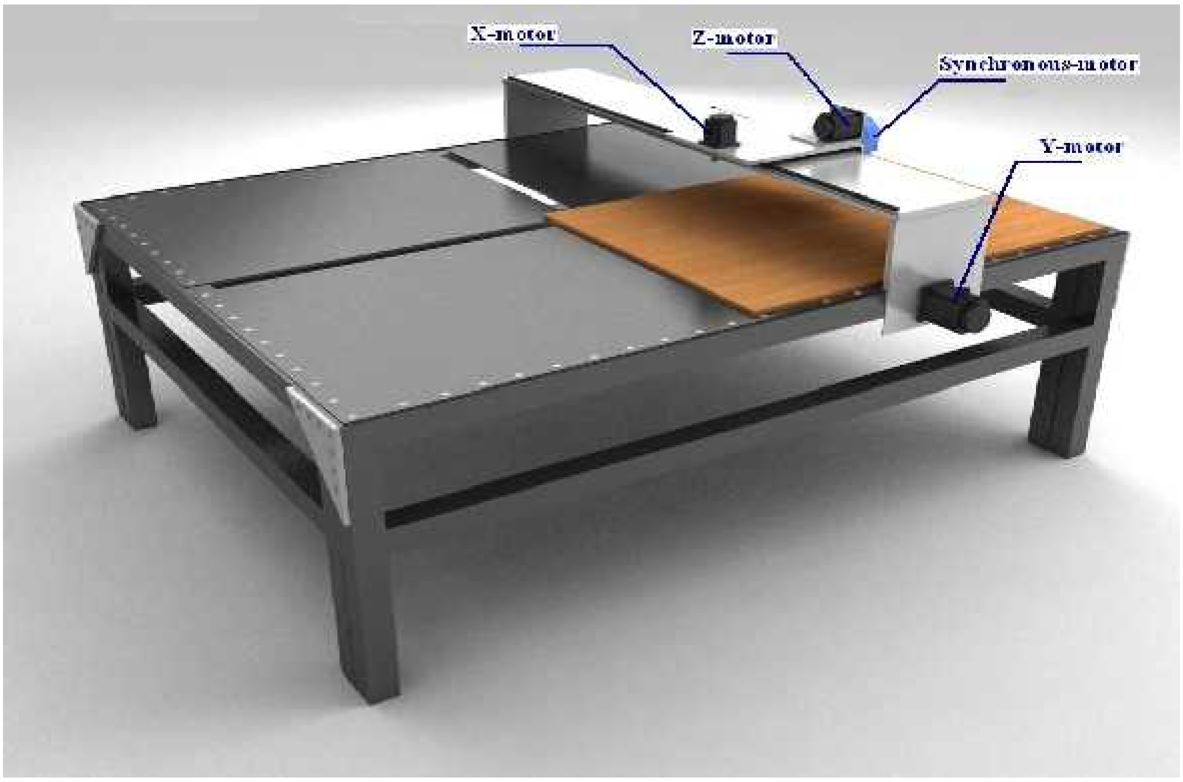



Figure 6.1: The body of automatic wood carving and decoration machine

*Note: to watch another pictures of the machine see Appendix C.*

## 6.2 Motor power calculations

The three AC servo motors use the rack and pinion gear to tangentially driven the load.

Let a mass (m) having a translation velocity ( $\dot{x}$ ) be coupled to another mass (of mass moment of inertia $J_0$) having a rotational velocity ( $\dot{\theta}$ ) as in the rack and pinion arrangement shown in Figure 6.2**.** These two masses can be combined to obtain either (1) a single equivalent translation mass *meq* or (2) a single equivalent rotational mass *Jeq* as shown below:

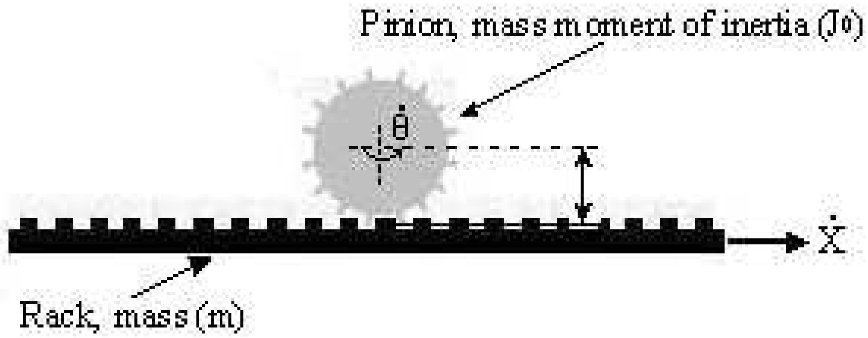



Figure 6.2: Translation and rotational masses in a rack and pinion arrangement

1. Equivalent translational mass. The kinetic energy of the two masses is given by:

$$T = \frac{1}{2} m \dot{x}^2 + \frac{1}{2} J_0 \dot{\theta}^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(6.1)}$$

and the kinetic energy of the equivalent mass can be expressed as:

$$T_{eq} = \frac{1}{2} m_{eq} \dot{x}^2_{eq} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6.2)$$

Since $\dot{x}^2_{eq} = \dot{x}$ and $\dot{\theta} = \dot{x} / R$, the equivalence of T and $T_{eq}$ gives:

$$\frac{1}{2} m_{eq} \dot{x}^2 = \frac{1}{2} m \dot{x}^2 + \frac{1}{2} J_0 \left( \frac{\dot{x}}{R} \right)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6.3)$$

That is,

$$m_{eq} = m + \frac{J_0}{R^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6.4)$$

2. Equivalent rotational mass. Here $\dot{\theta}_{eq} = \dot{\theta}$ and $\dot{x} = \dot{\theta} R$, and the equivalence of T and $T_{eq}$ leads to:

$$\frac{1}{2} J_{eq} \dot{\theta}^2 = \frac{1}{2} m (\dot{\theta} R)^2 + \frac{1}{2} J_0 \dot{\theta}^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6.5)$$

or

$$J_{eq} = J_0 + mR^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6.6)$$

### 6.2.1 Y-motor power calculation

The gear of the Y-motor with its load is shown in Figure 6.3:

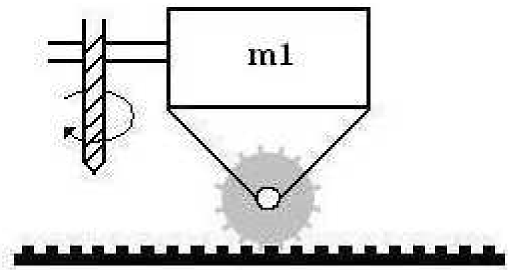



Figure 6.3: The Y-motor gear and its load without drilling operation

$$KE = \frac{1}{2}(J_m + J_p)\dot{\theta}^2 + \frac{1}{2}(m_m + m_p + m_1)\dot{x}^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \ (6.7)$$

We neglect the friction as we used a linear bearing but there is a viscous damping:

$$\text{Equivalent damping} = \frac{1}{2}C_{eq}\dot{\theta}^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \ (6.8)$$

(PE = 0).

Lagrange (L) = KE – PE…………………………………………………………… (6.9)

$$L = \frac{1}{2}\left[(J_m + J_p) + (m_m + m_p + m_1)r_p^{\,2}\right]\dot{\theta}^2 - 0$$

$$L = \frac{1}{2}\left[(J_m + J_p) + (m_m + m_p + m_1)r_p^{\,2}\right]\dot{\theta}^2$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) - \frac{\partial L}{\partial \theta} + \frac{\partial R}{\partial \theta} = T_d$$

$$\frac{\partial L}{\partial \dot{\theta}} = \left[\left(J_p + J_m\right) + (m_m + m_p + m_1)r_p^{\,2}\right]\dot{\theta}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) = \left[\left(J_p + J_m\right) + (m_m + m_p + m_1)r_p^{\,2}\right]\ddot{\theta}$$

$$\frac{\partial L}{\partial \theta} = 0$$

$$\frac{\partial R}{\partial \dot{\theta}} = C_{eq}\dot{\theta}$$

$$\left[\left(J_p + J_m\right) + (m_p + m_m + m_1)r_p^{\,2}\right]\ddot{\theta} + C_{eq}\dot{\theta}_a = T_d \quad \ldots\ldots\ldots\ldots\ldots\ldots \ (6.10)$$

Here the transverse force from the drilling tool is not included.

During drilling:

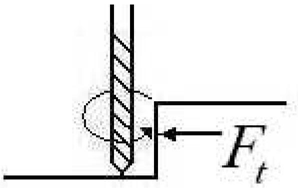



Figure 6.4: The transverse force during the drilling operation

Now additional torque required by the motor is:

$T_a = F_t r_p$ …………………………………………………………………… (6.11)

Where:

$T_a$ : The motor torque required to overcome the transverse force during the drilling process.

$F_t$ : The transverse force during the drilling operation.

$r_p$ : The pinion radius.

$$\left[\left(J_p + J_m\right) + (m_p + m_m + m_1) r_p^{\,2}\right]\ddot{}_{\,} + C_{eq}\dot{}_{a} = T_d - T_a$$

$$\therefore T_d = \left[\left(J_p + J_m\right) + (m_p + m_m + m_1) r_p^{\,2}\right]\ddot{} + C_{eq}\dot{} + T_a \quad \text{………………………… (6.12)}$$

Where:

$T_d$ : The driving torque of the motor.

$J_p$ : Pinion moment of inertia.

$J_m$ : Motor moment of inertia.

$m_p$ : Pinion mass.

$m_m$ : Motor mass.

$m_1$ : The mass of the load which the Y-motor drive.

$C_{eq}$ : Damping factor.

$m_1$ = m (linear bearing) +(X-linear bearing) + m (Z-linear bearing) + m (sliding bridges) + m (X-motor) + m (Z-motor) + m (rotating motor) + m(X-rack) + m (Z-rack).

m1 $\cong$ 22 Kg + (35+54 + 4 +32) Kg + 5 + 5 + 4 + 5 +3.

$\cong$ 169 Kg.

$m_m$ = 5 Kg.

$m_p$ = 0.2 Kg.

To calculate the pinion moment of inertia, let the pinion shape as in Figure 6.5:

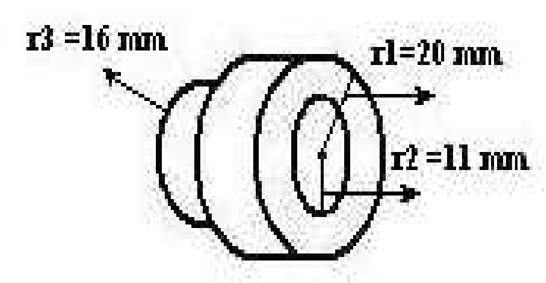



Figure 6.5: The pinion which coupled to the Y-motor

$$J = \int_0^m r^2 dM \quad \text{……………………………………………………………………..(6.13)}$$

$$J_p = \frac{1}{2}(r_1 - r_2)^2 m_{p1} + \frac{1}{2}(r_3 - r_2)^2 m_{p2} \quad \text{.............................................. (6.14)}$$

$$= 6.075\times10^{-6} + 12.5\times10^{-6}$$

$$\therefore J_p = 18.575\times10^{-6} Kg.m^2$$

To calculate the moment of inertia of the motor, let the shape of its rotor and its shaft as shown in the Figure 6.6:

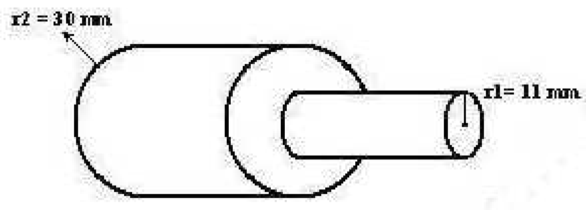



Figure 6.6: the Y-motor rotor with its shaft

$$J_m = \frac{1}{2}r_1^2 m_S + \frac{1}{2}r_2^2 m_r \quad \text{........................................................... (6.15)}$$

Where:

$m_S$ : The shaft mass.

$m_r$ : The rotor mass.

$$J_m = \frac{1}{2}(0.011)^2 0.3 + \frac{1}{2}(0.03)^2 0.8$$

$$= 1.815 \times 10^{-5} + 36 \times 10^{-5}$$

$$\therefore J_m = 37.815 \times 10^{-5} Kg.m^2$$

Let the maximum linear speed (V) of the load is 0.15 m/s, and the maximum acceleration (a) of the load is $0.25\, m/s^2$.

$$\dot{\theta} = \frac{V}{r_p} = \frac{0.15}{0.02} = 7.5 rad/s\ .$$

$$\ddot{\theta} = \frac{a}{r_p} = \frac{0.25}{0.02} = 12.5 rad/s^2\ .$$

(The value of $C_{eq}$ is determined experimentally by tangentially pulling the Y-motor load in a known constant speed ($\ddot{\theta}$ =0) using spring balance and measure the required force to move it)

$$C_{eq} \cong \frac{F_{mesured} \times r_p}{\dot{\theta}} \quad \text{......................................................................} \quad (6.16)$$

$$= \frac{27 \times 0.02}{1.5} = 0.36 \text{ N.m.s.}$$

Where:

$F_{mesured}$ : The value of the force which given from the spring balance.

$F_t \cong$ 95 N. (the value of $F_t$ is determined experimentally).

$\therefore T_a$ = 95 * 0.02 = 1.9 N.m.

$$T_d = \left[\left(18.757 \times 10^{-6} + 37.815 \times 10^{-5}\right) + (0.2 + 5 + 169) 0.02^2\right] 12.5 + 0.36 \times 7.5 + 1.9$$

$$= \left[39.69\times10^{-5} + 6.9\times10^{-2}\right]12.5 + 2.7 + 1.9$$

$$T_d = 5.4675 N.m$$

$$P_0 = T_d \times \mu_m \quad \ldots\ldots (6.17)$$

$$= 5.4675\times209.44$$

*The value of ( $\mu_m$ ) is taken from the data sheet.*

$$\therefore P_0 = 1145.1 \text{W}$$

$$P_m = 1.2 P_0$$

$$= 1.2\times1145.1$$

$$\therefore P_{my} = 1374 \text{ W}$$

Where:

$P_{my}$ : The Y-motor power.

$\mu_m$ : The Y-motor speed.

### 6.2.2 X-motor power calculation

The gear of the X-motor with its load is shown in Figure 6.7:

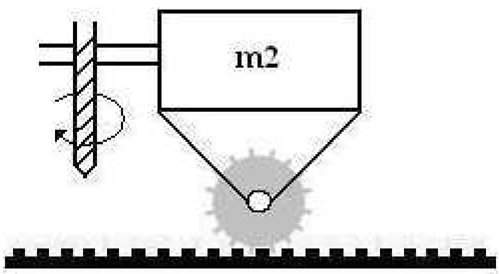



Figure 6.7: The X-motor gear and its load without drilling operation

The driving torque equation of the X-motor is:

$$T_d = \left[ \left( J_p + J_m \right) + (m_p + m_m + m_2) r_p^{\,2} \right] \ddot{\;} + C_{eq1} \dot{\;} + T_a \text{ ..............................} \quad (6.18)$$

Where:

$m_2$: The mass of the load which the X-motor drive.

$m_2$ = m (linear bearing) + m (Z-linear bearing) + m (sliding bridges) + m (X-motor) + m (Z-motor) + m (rotating motor) + m (Z-rack).

= 12+ (35+5) + 5+ 5+ 3+ 4+ 3

= 72 Kg.

$$C_{eq1} = \sim m_2$$

$$\sim = \frac{C_{eq}}{m_1} = \frac{0.36}{169} = 2.13 \times 10^{-3} N.s$$

$$C_{eq1} = 2.13 \times 10^{-3} \times 72$$

$$\therefore C_{eq1} = 0.1534 N.m.s$$

$$T_d = \left[ \left( 18.575 \times 10^{-6} + 37.815 \times 10^{-5} \right) + (0.2 + 5 + 58) 0.02^2 \right] 12.5 + 0.1534 \times 7.5 + 1.9$$

$$= \left[ 3.96 \times 10^{-4} + 3 \times 10^{-2} \right] 12.5 + 1.15 + 1.9$$

$$\therefore T_d = 3.43 N.m$$

$$P_0 = T_d \times \mu_m$$

$$= 3.43 \times 209.44$$

$$= 3.43 \times 209.44$$

$$\therefore P_0 = 718.5 \text{ W}$$

$$P_{mx} = 1.2 P_0$$
$$= 1.2 \times 718.5$$

$$\therefore P_{mx} = 862.13 \text{ W.}$$

Where:

$P_{mx}$ : The X-motor power.

$\mu_m$ : The X-motor speed.

### 6.2.3 Z-motor power calculation

The gear of the Z-motor with its load is shown in Figure 6.8:

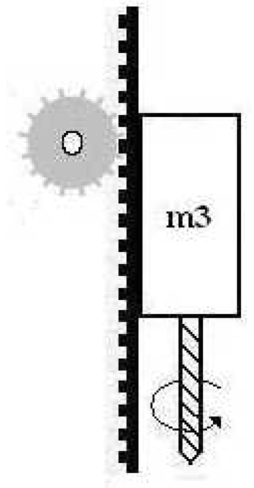



Figure 6.8: The Z-motor gear and its load without drilling operation

$$KE = \frac{1}{2}\left[(J_p + J_m) + (m_R + m_3) r_p{}^2\right] \dot{-}^{2} \quad \text{…………………………………………} \ (6.20)$$

(PE = 0).

Lagrange (L) = KE – PE

$$L = \frac{1}{2}\left[(J_p + J_m) + (m_R + m_3)r_p{}^2\right]\dot{\bar{\ }}^2 - 0$$

$$L = \frac{1}{2}\left[(J_p + J_m) + (m_R + m_3)r_p{}^2\right]\dot{\bar{\ }}^2$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\bar{\ }}}\right) - \frac{\partial L}{\partial \bar{\ }} - \frac{\partial R}{\partial \dot{\bar{\ }}} = T_d$$

$$\frac{\partial L}{\partial \dot{\bar{\ }}} = \left[\left(J_p + J_m\right) + (m_R + m_3)r_p{}^2\right]\dot{\bar{\ }}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\bar{\ }}}\right) = \left[\left(J_p + J_m\right) + (m_R + m_3)r_p{}^2\right]\ddot{\bar{\ }}$$

$$\frac{\partial L}{\partial \bar{\ }} = 0$$

$$\frac{\partial R}{\partial \dot{\bar{\ }}} = C_{eq}\dot{\bar{\ }}$$

$$T_d = \left[\left(J_p + J_m\right) + (m_R + m_3)r_p{}^2\right]\ddot{\bar{\ }} + C_{eq2}\dot{\bar{\ }} + T_b + m_3 \times g \times r_p \text{ …………………. (6.21)}$$

Where:

$m_3$ : The mass of the load which the X-motor drive.

$m_R$ : The Z-rack mass.

$g$ : The gravity acceleration.

$$T_b = F_b \times r_p \text{ ……………………………………………………………….... (6.22)}$$

Where

$F_b$ : The drilling force.

$T_b$ : The torque required to overcome the drilling force.

$m_3$ = m (linear bearing) + m (sliding bridge) + m (rotating motor).

=1 + 2 + 3

= 6 Kg.

Let $F_b$ =110N

$$C_{eq2} = \sim m_3$$

$$= 2.13 \times 10^{-3} \times 6$$

$$\therefore C_{eq2} = 0.0128 N.m.s$$

$$T_d = \left[3.96 \times 10^{-4} + (3+6)0.02^2\right]12.5 + 0.0128 \times 7.5 + 2.2 + 6 \times 9.81 \times 0.02$$

$$= 0.05 + 0.096 + 2.2 + 1.177$$

$$\therefore T_d = 3.523 N.m$$

$$P_0 = T_d \times \mu_m$$

$$= 3.523 \times 209.44$$

$$\therefore P_0 = 737.86\,\text{W}$$

$$P_m = 1.2 P_0$$

$$= 1.2 \times 737.86$$

$$\therefore P_{mz} = 885.43\,\text{W}.$$

### 6.2.4 AC synchronous motor power

The power of the AC synchronous motor (rotating motor) is chosen experimentally and the value of it equal to (370W).

The name plate of this motor is shown in table 6.1:

Table 6.1: AC synchronous motor name plate:

| | | | |
|---|---|---|---|
| **E.M.G.** | | **ELCTROMECCANICA** | |
| **Tel.0444/295111-GAMBUGLIANO(VI) ITALY** | | | |
| Tipo | 71/2 | Num. 665y55960 | |
| V Δ | 230-265 | V ⅄ | 400-460 |
| KW | 0.37-0.4 | A | 1.9/1.1 |
| RPM | 2810-3370 | *C* os¤ | 0.65 |
| Hz | 50/60 | Ip | 55 |
| | | 3-ph | |
| | | CL | F |
| Made in ITALY | | IEC60034 | |

### 6.3 Machine amplifiers

The voltage out from the interfacing circuit is represented as a (5 V), this value isn’t sufficient to control the motors operations, so as to the voltage from the interfacing circuit must be amplified.

Each motor needs (24 V DC) to control its processes, so the request amplifier amplifies the signal from (5V) to (24V), as shown in Figure 6.9:

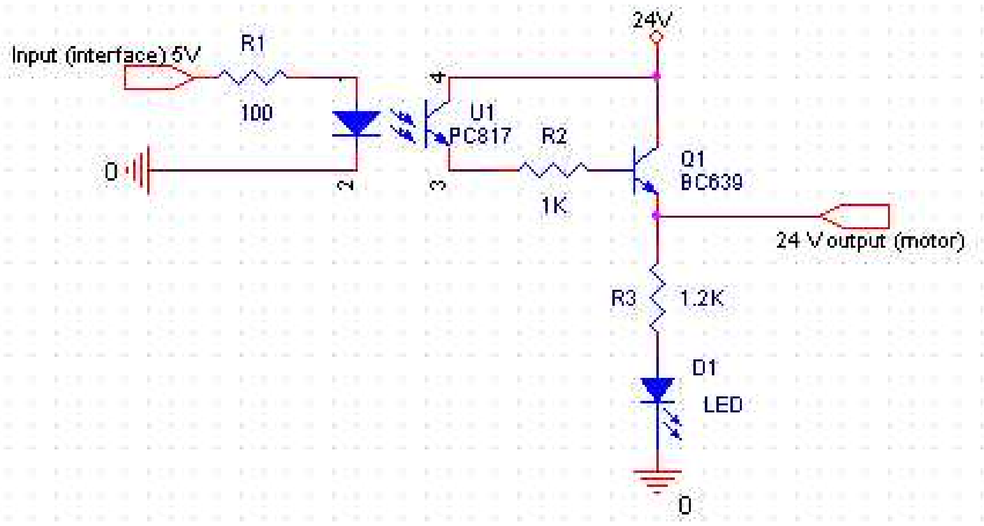


Figure 6.9: The machine amplifier circuit

The maximum voltage of the Optucoupler is (2.2 V), and the maximum current of the LED is (20 mA).

$$I_1 \times R1 + 2.2 = 5 \quad (6.23)$$

$$0.02 \times R1 + 2.2 = 5$$

$$(R1 = 140\Omega)$$

$$24 = 0.02R2 \quad (6.24)$$

$$(R2 = 1.2K\Omega)$$

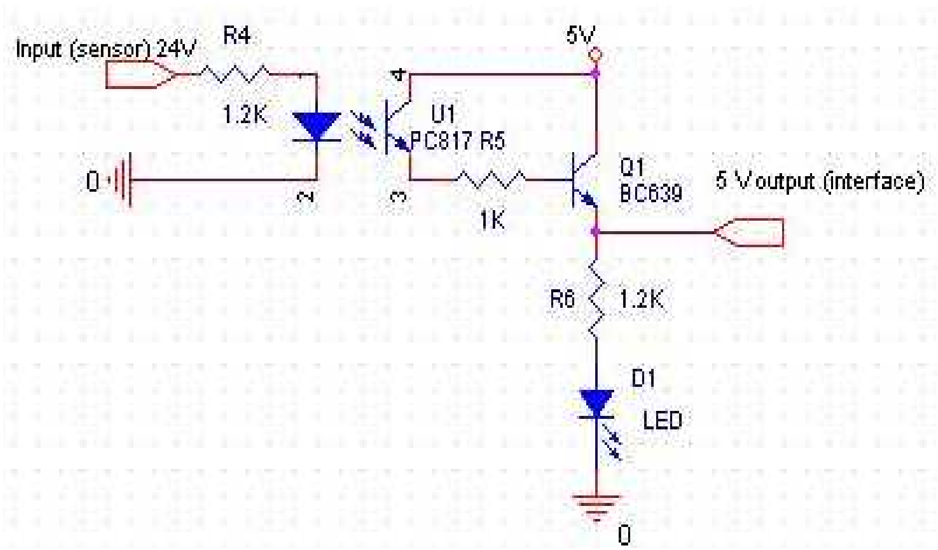



Figure 6.10: The voltage decreasing circuit

$I_2 \times R4 + 2.2 = 24$ ……………………………………………………..……. (6.25)

$0.02 \times R4 + 2.2 = 24$

$\therefore (R4 = 1090\Omega)$

$5 = 0.02R6$ ……………………………………………..……..………… (6.26)

$\therefore (R6 = 250\Omega)$

*Note1: The layout of these circuits is shown in Appendix A.*

*Note 2: to see the machine amplifier circuits after constructing them practically, return to Appendix C.*

### 6.4 Design of beams and legs of the machine

Beams and legs of the machine are designed according to the load and resistance factor method LRFD specification for structural steel construction (1995) by the American institute of steel structure AISC.

### 6.4.1 Load analysis

Dead load = Plates + Beam.

Live load = moving motors + wood plate.

Dead load (D) = 300 kg.

Live load (L) = 500 Kg.

The load will be transfer to the (2.5m) length beam across the short length of the machine.

$$D = \frac{mass}{Length} \quad \text{.......... (6.27)}$$

$$D = \frac{300Kg}{2.5m} = 120Kg/m.$$

$$L = \frac{mass}{Length}$$

$$L = \frac{500Kg}{2.5m} = 200Kg/m.$$

Factored load:

$$q_u = 1.2D + 1.6L \quad \text{.......... (6.28)}$$

= 1.2 (120) + 1.6 (200)

$= 464.0Kg/m$

### 6.4.2 Design of beam

a. Design of the moment:

Assume compact section method:

¤$.M_n \geq M_u$

$M_n = f_y . z_x$ ……………………………..……………………………………… (6.29)

¤$.f_y . z_x \geq M_u$

$M_u = 362.5 Kg.m$ (see the moment diagram in Figure 6.11)

$f_y = 280 MPa = 280 \times 10^5 Kg / m^2$

¤ $= 0.9$ (reduction factor of nominal moment).

$$\therefore z_x \geq \frac{362.5 Kg.m}{0.9 \times 280 \times 10^5 Kg / m^2}$$

$$= 14.3 cm^3$$

Select tube $(60mm \times 60mm \times 3.25mm)$

$z_{xprovided} = 17.0 cm^3$

$z_{xprovided} > z_{xreq.}$

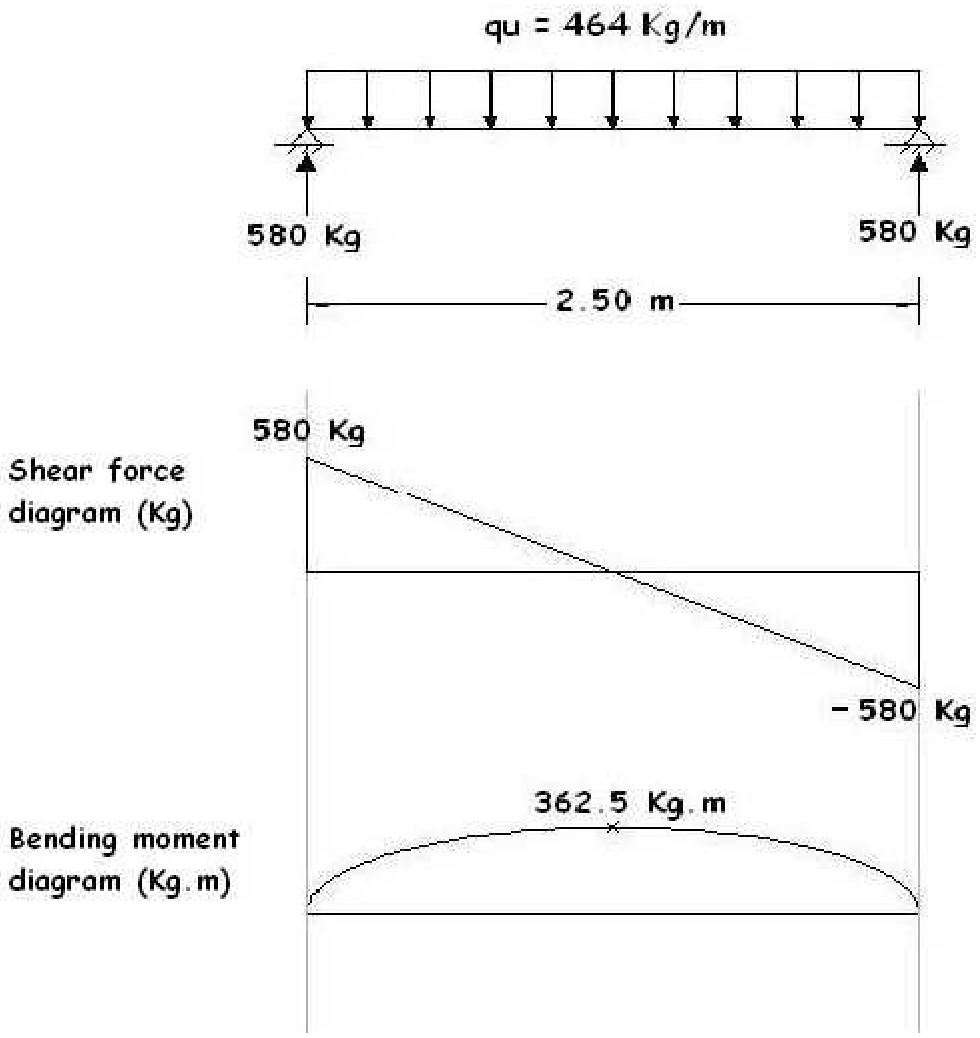



Figure 6.11: Bending moment and shear force diagram

b. Design of shears:

$\phi . V_n \geq V_u$

$V_n = f_y . h_c . t_w$ ………………………………………………………………….. (6.30)

$\phi . f_y . h_c . t_w . V_n \geq V_u$

$V_u = 580 Kg$ (see the shear force diagram in Figure 6.11)

$f_y = 280 \times 10^5 Kg / m^2$

$h_c = 0.06m$ (for the selected profile).

$t_w = 0.035$ (for the selected profile).

¤ $= 0.75$ (reduction factor of the nominal shear).

$\therefore 0.75 \times 280 \times 10^5 \times 0.06 \times 0.035 \geq 580Kg$

c. Design of the deflection:

¢$_{max}$ (For nominal dad and live load) $\leq \frac{L}{360}$ (for simply supported beams).

$$\leq \frac{2.5 \times 10^3 mm}{360}$$

$$\leq 7.0mm$$

$$¢_{max} = \frac{5 \times q \times L^4}{384 \times E \times I} \quad \text{.......................................................................} \quad (6.31)$$

$q = 464Kg/m$

$I_{provided} = 1966 \times 10^{-8} m^4$

$E = 200GPa$

$E = 2 \times 10^{10} Kg/m^2$

$$\therefore ¢_{max} = \frac{5 \times 464 \times 2.5^4}{384 \times 2 \times 10^{10} \times 1966 \times 10^{-8}}$$

$$= 6 \times 10^{-4} m$$

$$= 0.6mm < 0.7mm.$$

### 6.4.3 Design of the support

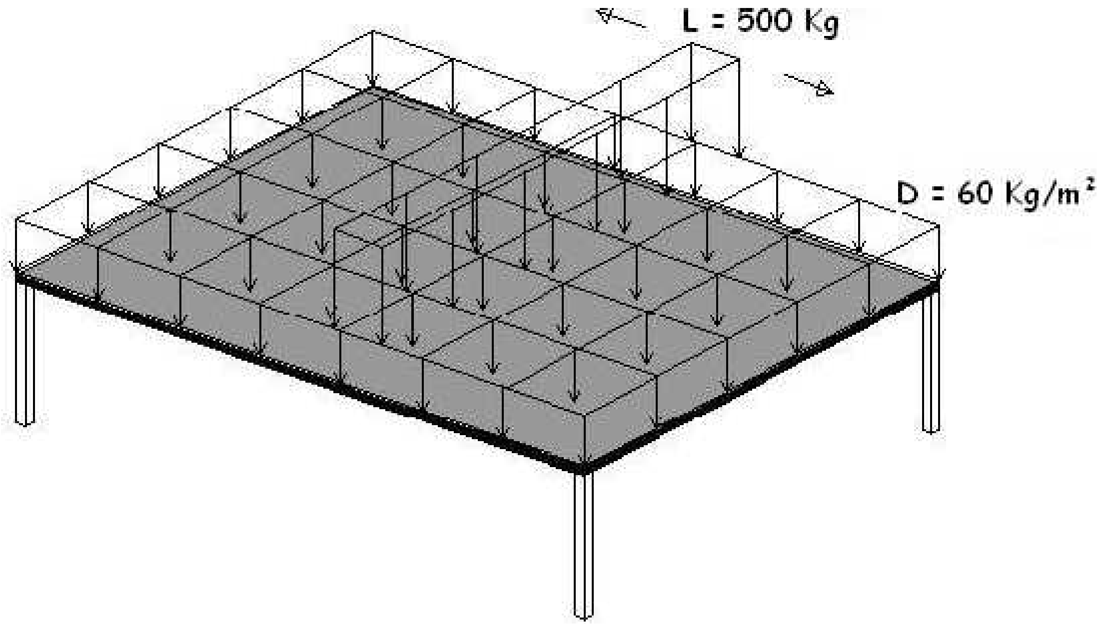



Figure 6.12: Machine supports

¤$.p_n \geq p_n$

$p_n = 580Kg$

Effective length factor $\left(k_x = k_y = 1.0\right)$

$L_x = L_y = 90cm = 0.9m$

$k_x .L_x = k_y L_y = 1 \times 0.9 = 0.9m$

Assume $\frac{K_L}{r} = 100$

Where: r is the modulus of gyration.

$F_{critical}$ @ $\left(\frac{K_L}{r} = 100\right) = 151.7MPa$

$= 151.7 \times 10^5 Kg / m^2$

$$\text{¤}.p_n \geq p_u$$

$$p_n = F_{critical} \times Ag_{req.} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6.32)$$

$$\therefore \text{¤}.F_{critical}.Ag_{req.} \geq p_n$$

$$Ag_{req.} = \frac{p_n}{\text{¤}.F_{critical}}$$

$$= \frac{580}{0.85 \times 151.7 \times 10^5}$$

$$= 4.5 \times 10^5 m^2$$

$$= 45 mm^2$$

Select tube $\left(60mm \times 60mm \times 3.25mm\right)$

$$A_{g_{provided}} > A_{g_{req.}}$$

# Chapter 7
# Interface Design and Testing

## 7.1 Introduction to parallel port

The parallel port is the most commonly used for interfacing different projects especially home project. The port will allow the input of up to 8 bits or the output of 12 bits at any one given time, thus requiring minimal external circuitry to implement many simpler tasks. The port is composed of 4 control lines, 5 status lines and 8 data lines. It is found commonly on the back of our PC as a D-Type 25 Pin female connector. There may also be a D-Type 25 pin male connector.

Newer parallel ports are standardized under the IEEE 1284 standard first released in 1994. This standard defines 5 modes of operation, which are as the following:

- Compatibility Mode.
- Nibble mode.
- Byte mode.
- EPP mode (Enhanced Parallel Port).
- ECP mode (Extended Capabilities Mode).

The aim was to design new drivers and devices, which were compatible with each other and also backwards compatible with the standard parallel port (SPP). Compatibility, Nibble and Byte modes use just the standard hardware available on the original parallel port cards while EPP and ECP modes require additional hardware which can run at faster speeds, while still being downwards compatible with the standard parallel port.

Compatibility mode or "Centronics Mode" as it is commonly known can only send data in the forward direction at a typical speed of 50 Kbytes per second but can be as high as 150 Kbytes per second. In order to receive data, we must change the mode to either Nibble or Byte mode. Nibble mode can input a nibble (4 bits) in the reverse direction. e.g.; from device to computer. Byte mode uses the parallel's bi-directional feature (found only on some cards) to input a byte (8 bits) of data in the reverse direction.

Extended and Enhanced parallel ports use additional hardware to generate and manage handshaking. To output a byte to a printer (or anything in that matter) using compatibility mode, the software must,

1. Write the byte to the data Port.
2. Check printer status. If the printer is busy, it will not accept any data, thus any data, which is written, will be lost.
3. Take the strobe (Pin 1) low. This tells the printer that there is the correct data on the data lines (Pins 2-9).
4. Put the strobe high again after waiting approximately 5 microseconds after putting the strobe low.

This limits the speed at which the port can run at. The EPP and ECP ports get around this by letting the hardware check to see if the printer is busy and generate a strobe and /or appropriate handshaking. This means only one I/O instruction need to be performed, thus increasing the speed. These ports can output at around 1-2 megabytes per second. The ECP port also has the advantage of using DMA (Direct Memory Access) channels and FIFO (First In First Out) buffers, thus data can be shifted around without using I/O instructions.

### 7.2 Hardware properties

Below is a table of the "Pin Outs" of the D-Type 25 pin connector and the centronics 36 pin connector. The D-Type 25 pin connector is the most common connector found on the parallel port of the computer, while the centronics connector is commonly found on printers.

Table 7.1: Pin assignments for parallel port connector

| D-25 type | Centronics 36 type | SSP function | Direction | Register | Invert |
|---|---|---|---|---|---|
| 1 | 1 | Strobe | In/Out | Control | ✓ |
| 2-9 | 2-9 | Data lines | Out | Data | |
| 10 | 10 | Acknowledge | In | Status | |
| 11 | 11 | Busy | In | Status | ✓ |
| 12 | 12 | Out of Paper | In | Status | |
| 13 | 13 | Select | In | Status | |
| 14 | 14 | Auto feed | In/Out | Control | ✓ |
| 15 | 15,32 | Error | In | Control | |
| 16 | 16,31 | Init | In/Out | Status | |
| 17 | 17,36 | Select In | In/Out | Status | ✓ |
| 18-25 | 18-30,33 | GND | Gnd | | |
| - | 34,35 | N/C | Gnd | | |

The IEEE 1284 standard however specifies 3 different connectors for use with the parallel port. The first one, 1284 Type A is the D-Type 25 connector found on the back of most computers. The second is the 1284 Type B, which is the 36 pin centronics connector.

IEEE 1284 Type C however, is a 36 conductor connector like the centronics, but smaller. This connector is claimed to have a better clip latch, better electrical properties and is easier to assemble. It also contains two more pins for signals which can be used to see whether the other device connected, or has power. 1284 Type C connectors are recommended for new designs, so we can look forward on seeing these new connectors in the near future.

The letter used "n" in front of the signal name to denote that the signal is active low. If the printer encounters an error then this line is low. This line normally is high, should the printer be functioning correctly. The "Hardware Inverted" means the signal is inverted by the parallel card's hardware, such as busy line. If +5v (Logic 1) was applied to this pin and the status register read, it would return back a 0 logic in bit 7 of the status register.

The output of the parallel port is normally TTL logic levels. The current you can sink and source varies from port to port. Most parallel ports implemented in ASIC, can sink a source around 12mA; however some of them, sink/source 6mA, source 12mA/sink 20mA, sink 16mA/source 4mA, sink/source 12mA. As we can see they vary quite a bit. The best is to use a buffer, so the least current is drawn from the parallel port. Figure 7.1 shows the details about the parallel port.

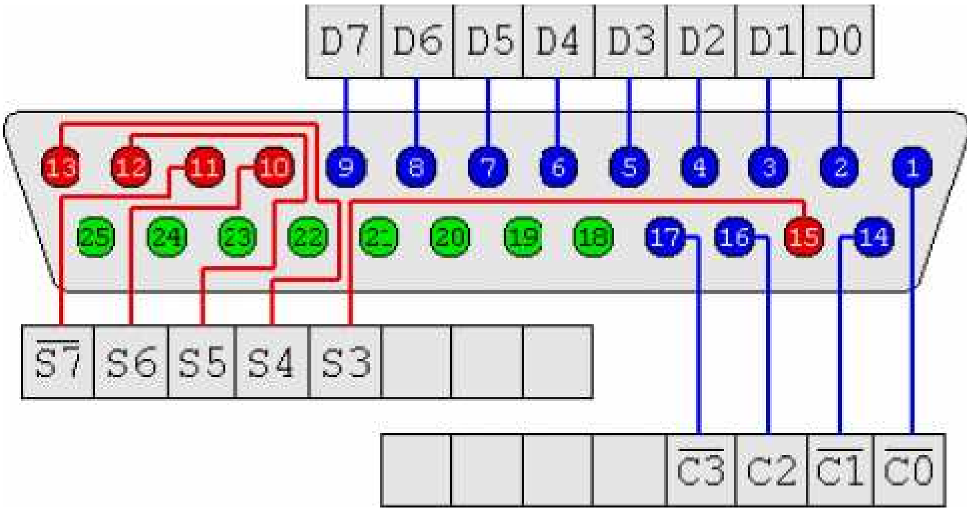



Figure 7.1: 25-way female D-type connector

- 8 output pins accessed via the data port (pin#2 – pin#9)
- 5 input pins (one inverted) accessed via the status port (pin#10 – pin#13, pin#15)
- 4 output pins (three inverted) accessed via the control port (pin#1, pin#14, pin#16, pin#17)
- The remaining 8 pins are grounded (pin#18 – pin#25)

### 7.3 Interface circuit objectives

The main objectives behind the interface circuit are:

1. Controlling the power circuit that consists of motors to move into 3-dimension.
2. Inputs to the power circuit from package software run on PC computer via parallel port.

3. Inputs from power circuit via driver to reflect the motor state and then from interface circuit to the parallel port and finally this informative signal resulted into massage in the program software to issue an action.
4. Isolating low-level voltage signal comes from parallel port from high-level voltage signal available in the motor drivers.

### 7.3.1 Interface circuit block diagram

Figure 7.2 represents both forward and backward interface circuit.

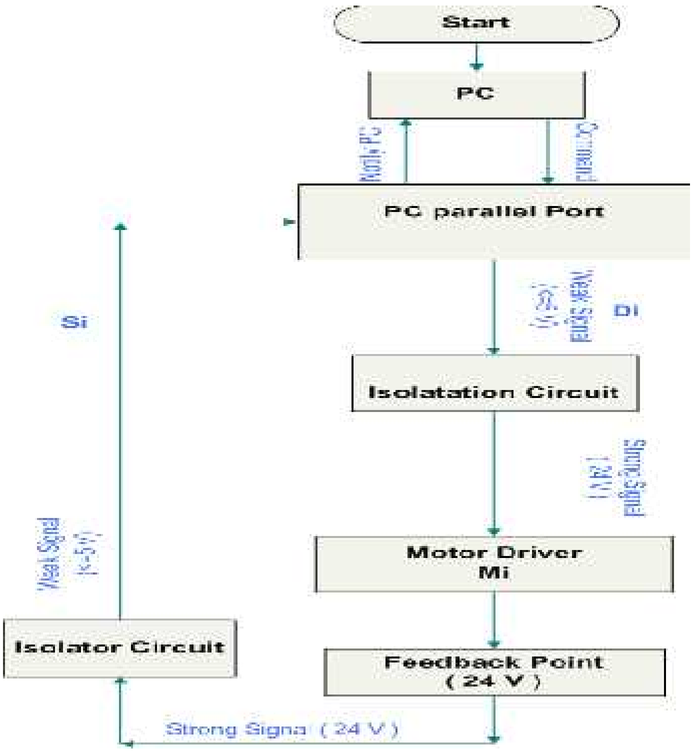



Figure 7.2: Interface circuit block diagram

### 7.3.2 How interface circuit works

The interface circuit is designed mainly to support the following two functions:

- The interface circuit is designed such that support receiving signal from PC package software via parallel port to provide the availability of 24 volt dc on the driver that would trigger the motor to work into the required direction if the signal on the port is logic 1.
- The interface circuit is designed such that support receiving signal from power circuit by virtue of some errors occurs in the power circuit reflected by the availability of 24 volt dc on motor driver.

### 7.4 Basic circuit with opt-isolation

Below is simple example of opt-isolated output circuit for parallel port based on 4N25 opt-coupler or 4N26.

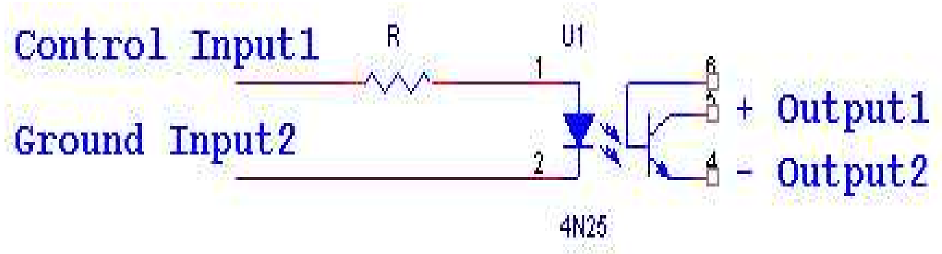



Figure 7.3: Basic circuit with opt-coupler

The above opt-isolator is to protect the ports, no connection between port's electrical contacts. The circuit is powered from external power supply, which is not connected to PC. This arrangement prevents any currents on the external circuits from damaging the parallel port.

The opt-isolator's input is a light emitting diode; R resistor is used to limit the current when the output from the port is on.

The output side of the opt-isolator is just like a transistor with the collector at the top of the circuit and the emitter at the bottom. When the output is turned on (by the input light from the internal LED in the opt-coupler), current flows through the resistor and into the transistor turning it on. This allows current to flow into output circuit; the output current from the opt- coupler should be around range (depending on exact opt-isolator type and components variations).

Turning the input on the parallel port off causes the output of the opt-isolator to turn off, so no current flows through it into the transistor and the transistor turns off. When transistor is off no current flows into the output driver circuit. So o it switches off.

## Characteristics:

- The 4N25 opt-coupler device has a driving current reach at max 60mA (forward current).
- The maximum voltage output that can isolate reach 450V.
- Input1 can be attached to the controlling signal like parallel port, while input2 is grounded with parallel port ground, and outputs to the circuit to be controlled at the right polarity.
- Between the controlling device and opt-coupler input1 there is resistor R that works as current limiter to protect the opt-coupler LED.
- The two terminal input and output is electrically isolated.
- Switching can be achieved while maintaining high degree of isolation between driver and load circuits.
- Very high current transfer 500% and also high isolation resistance.

## 7.5 Circuit design

We divided the design into two main parts:

- Forward interface circuit.
- Backward interface circuit.

### 7.5.1 Forward circuit calculation

In order to design the forward controlling circuit we need to do some calculations; this calculation related with resistor that limits the current.

From the datasheet the maximum barrier voltage of the driving LED bears reach 2 volt, and the maximum current that can flow in from input1 to ground input2 is at maximum 60mA, and the voltage output from parallel port is about 5 volt or less than, and taking the forward current less than or equal to 60 mA eg; 60mA.

According to the ampere's low

$V = I \times RLimit$ ……………………………………………(ampere's low)

By substitution in equation (1),

RLimit= (V- VBarrier)/I >>RLimit = (5-2) V/60mA=50Ω

So we found that RLimit must be equal to 50Ω, according to these calculations we designed the forward interface circuit

### 7.5.2 Backward circuit calculations

In order to design the backward controlling circuit we need to do some calculations; this calculation related with resistor that limits the current.

From the datasheet the maximum barrier voltage the driving LED bears reach 2 volt, and the maximum current that can flow in from input1 to ground input2 is at maximum 60mA, and the voltage input from driver is 24 volt, and taking the forward current less than or equal to 60 mA eg; 9.36mA.

According to the ampere's low

$V = I \times RLimit$ ………………………………………… (Ampere's low)

By substitution in equation (1),

$RLimit = (VDriver - VBarrier)/I$ >>$RLimit = (24-2)\ V/9.36mA = 2.35k\Omega$.

So we found that RLimit must be equal to 2.3kΩ, according to these calculations we designed the backward interface circuit.

By combining both forward circuit and backward circuit, we will produce the interface circuit that serves the following functions:

- Isolate the low voltage signal from high voltage signal of power circuit.
- The interface circuit will works in forward as switch (logic1 or logic 0).
- Backward circuit works as switch (availability of 24 volt or not).

So the interface circuit design is shown below in the figure 7.4.

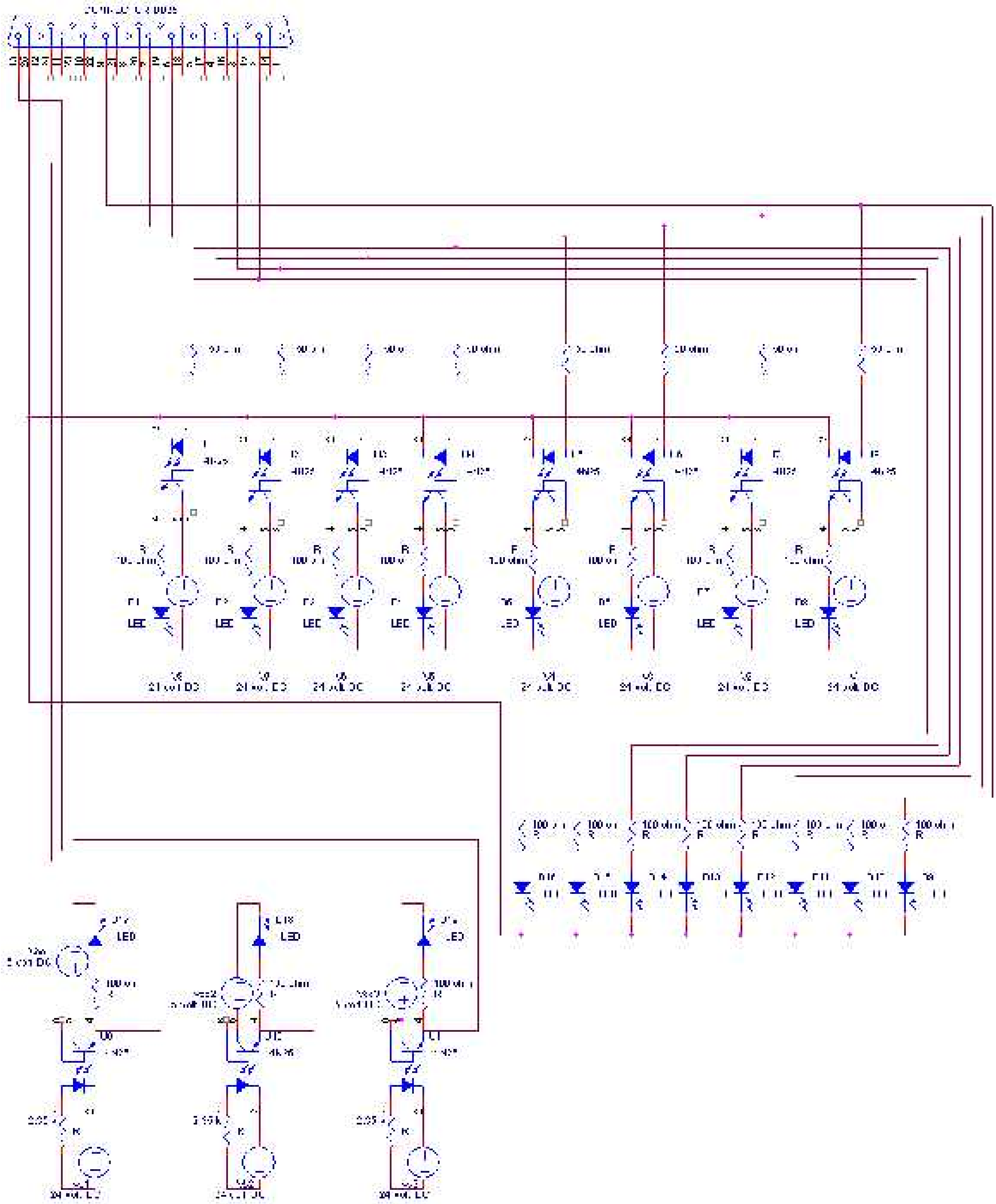


Figure 7.4: Interface circuit design

### 7.6 The board shape

After constructing the full design of interfacing circuit that consist of forward interfacing circuit and backward circuit; we obtained the following board. The board of interface circuit is shown in figure 7.5 below.

Figure 7.5: Board shape

### 7.7 Optucoupler description

An opt-coupler, also called optoisolator, is an electronic component that transfers an electrical signal or voltage from one part of a circuit to another or from one circuit to another, while electrically isolating the two circuits from each other. It consists of an infrared emitting LED chip that is optically in-line with a light-sensitive silicon semiconductor chip, all enclosed in the same package. The silicon chip could be in the form of a photo diode, photo transistor, photo Darlington.

#### 7.7.1 Optucoupler function

- To isolate one section of a circuit from another, each section having different signal voltage levels to ensure compatibility between them.
- To prevent electrical noise or other voltage transients that may exist in a section of a circuit from interfering with another section when both sections have a common circuit reference. Noise or voltage transients can be caused by a poor printed circuit board layout.

#### 7.7.2 Principle of operation

When a forward bias voltage is applied to the input terminals of the LED (positive to the anode), an input current, and limited by the series resistor, RS, will flow in the LED circuit. The current produces the infrared light emission at about 900 nanometers that impinges on the photosensitive silicon chip.

On the other hand, Optucoupler are similar in its operation; it differs in its types.

### 7.8 Testing interface circuit

### 7.8.1 Testing the forward interface circuit

The forward interface circuit is consisting of 8-lines from PC parallel port to the power circuit.

The eight lines begin from D0 up to D7 until it reaches the driver that will trigger the motors. The Figure 7.6 below shows the circuit for forward interface circuit taking the D0 as an example.

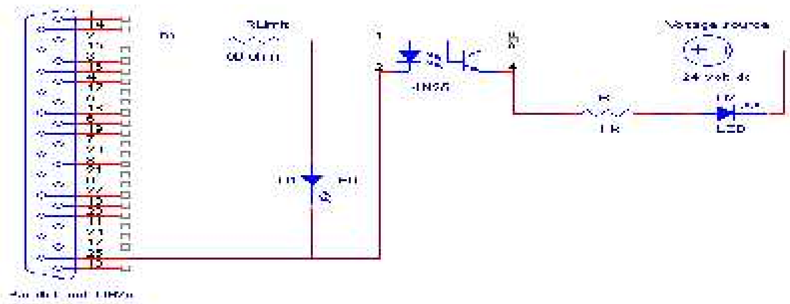


Figure 7.6:D0 data line for forward interface circuit

When we apply an output logic 1(+ 5volt) from PC parallel port through D0 as a data output line, current flow in forward section of opt-coupler limited by RLimit as a result the backward section of opt-coupler is switched on and also when apply logic 0 the backward section is switched off so no current flows in both two section, pin#25 of parallel port is ground of forward section of opt-coupler.

We design the following program to investigate the result; we found that the forward circuit works properly for D0 as a first data line. The Figure 7.7 below shows the result.

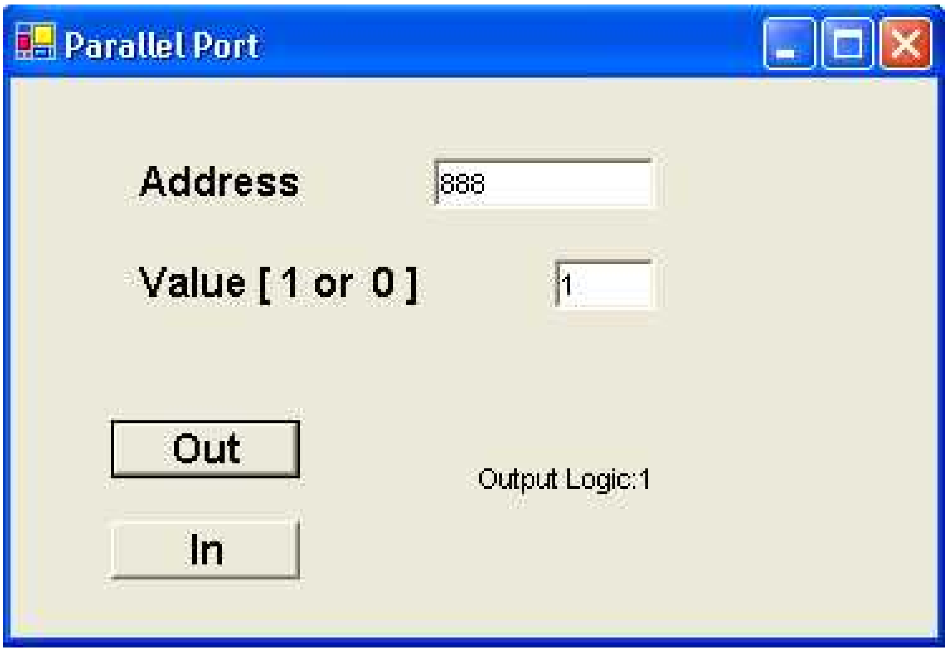



Figure 7.7: Do data result from circuit

Also we have seen the output of the circuit on board, the following Figure 7.8 illustrate the result using power supply 24 volt adjusted on the driver.

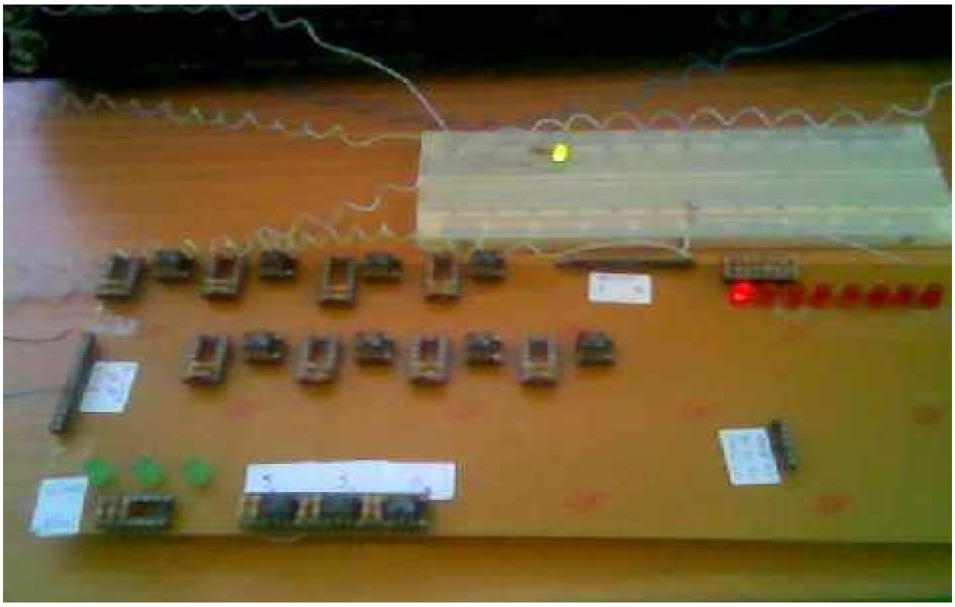


Figure 7.8:D0 result output

With same approach we used hardware duplication to build the rest of the forward circuit beginning from D0 up to D7 that consume the pins number pin#2 up to pin#9 respectively.

By the same way we built the interface circuit in forward by duplication of the previous state for D1, D2, D3, D4, D5, D6 and D7, and when the address of port begins with 888 decimal (378H) we increment it by one for each bit, e.g.; D1 take the address 889 until we reach D7 that take the address 896.and the result of connection is reflected also by parallel port pins from pin#2 for D0 until pin#9 for D7.

### 7.8.2 Testing the backward interface circuit

The backward interface circuit is consisting of 3-lines from the power circuit to parallel port.

The three lines begin from S1 up to S3 to reflect the availability of driver voltage in order to notify the computer system via a signal entered from parallel port status lines the Figure 7.9 below show the circuit for backward interface circuit taking the S1 as an example.

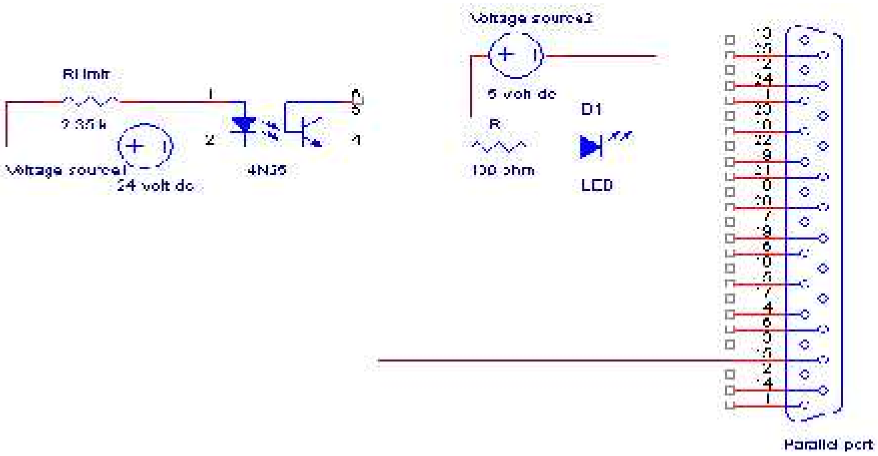



Figure 7.9: S1 status line for backward interface circuit

When we apply an input voltage 24 volt dc on the driver from motor, current flow in forward section of opt-coupler limited by RLimit as a result the backward section of opt-coupler is switched on and also when apply 0 volt dc the backward section is switched off so no current flows in both two section. After the availability of 24 volt dc on the opt-coupler terminal the backward section is fed by 5 volt to close the circuit with parallel port status lines to input logic 1 when 24 volt dc available and to input 0 logic when the no voltage available at the motor driver.

Also we have seen the output of the circuit on board, the following Figure 7.10 illustrate the result using power supply 24 volt adjusted on the driver an input signal to opt-coupler.

Figure 7.10:S1 result output

By the same way we investigate the result of s2 and s3 as a status input lines.

Note: S2 is connected to 13 and S3 is connected to 12 of parallel port pins.

# Chapter 8

# Practical Results

## 8.1 Results

The following points summarize the important results out from the project:

1. from the driving torque equation of the AC servo motor in the automatic carving and decoration machine we note that:

$$T_d = \left[ \left( J_p + J_m \right) + (m_p + m_m + m_1) r_p^{\,2} \right] \ddot{\vec{\ }} + C_{eq} \dot{\vec{\ }} + T_a$$

2. If the motor move in constant speed ( $\ddot{\vec{\ }}$ =0) and the drilling tool doesn’t carve on the wood board ( $T_a$ =0), then the only torque affect the motor torque is that from the equivalent damping ( $C_{eq} \dot{\vec{\ }}$ ), so its value is important and can't be neglected.

3. The automatic carving and decoration machine needs a fast response motors which make the acceleration and deceleration time very small, and so the error reduced, the accuracy increased, and the shape on the computer drawing program corresponding that the machine carving on the wood.

4. The operation of the automatic carving and decoration machine require a position control than a speed control, so the selected mode of the servo motor is the position mode.

5. The speed of the AC synchronous motor (drilling tool rotating speed) is constant to all type of the wood, but the speed of the three AC servo motors is

changing with each type of the wood and set manually on the drive of each motor.

6. To control the position of the Ac servo motor we need two input on the servo drive, one to determine the direction of the motor (CW and CCW), and the other to determine the position of the motor (pulse input).

7. Each (10 pulse) entered the pulse input of the motor from the interfacing circuit move the load (1mm), and the corresponding between this scale and machine scale can be set using the electronic gear ratio on the motor drive(changing the resolution).

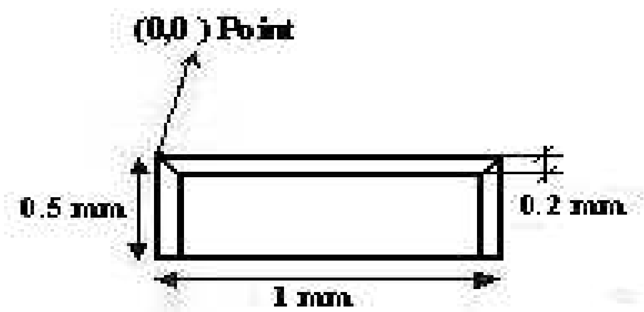
8. We can move the AC servo motor manually using the (JOG) operation on the motor drive.

9. The frequency of pulse entered the motor drive determine the motor speed.

10. The smallest linear distance the load can move is (1mm), as the distance between the pinion teeth is (1mm).

## 8.2 Machine motors signals

To illustrate the nature of signals must be provided to the machine motors when it carving a shape on the wood, we employed the following two examples:



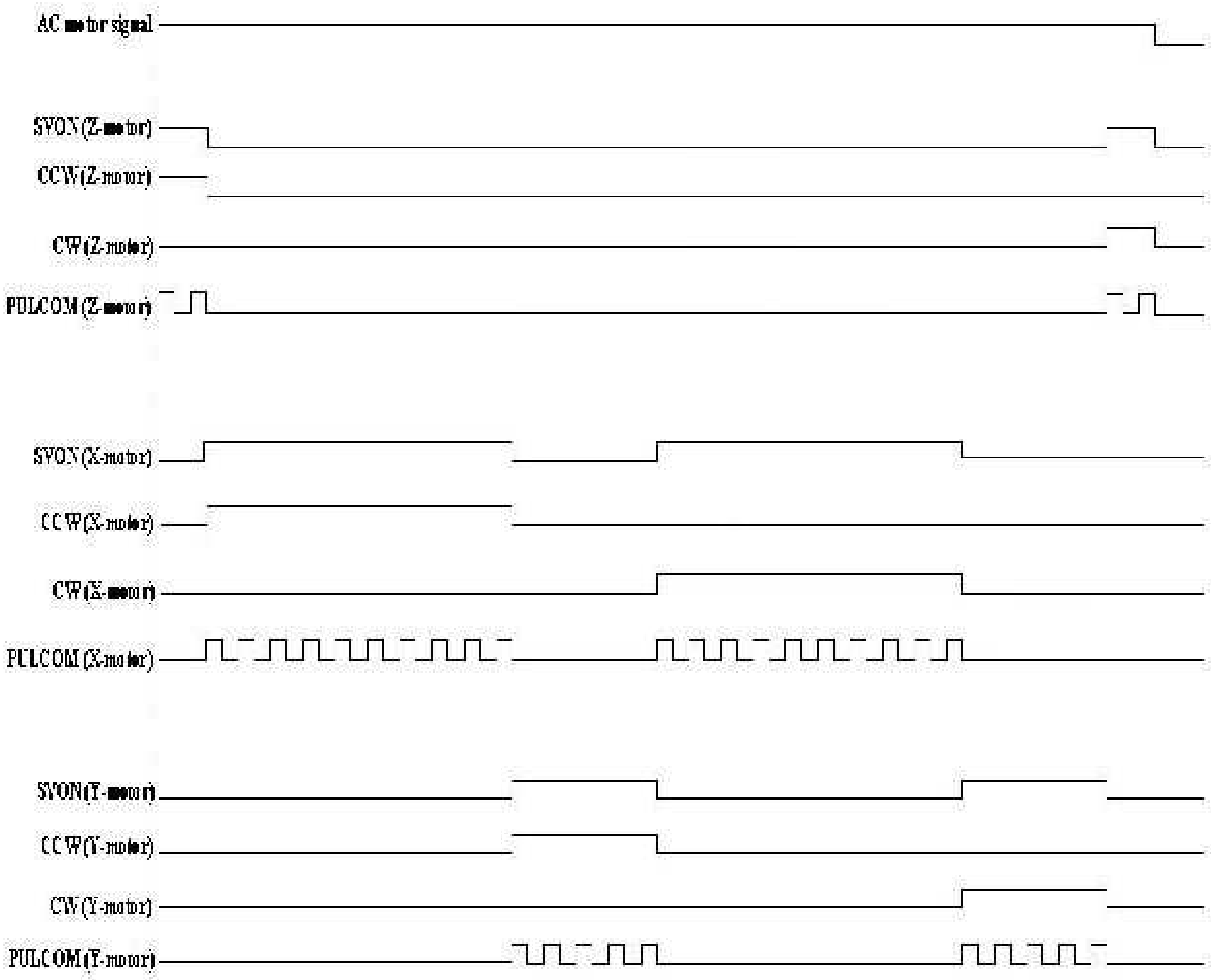


Figure 8.1: motor signals when the machine carving a rectangular shape

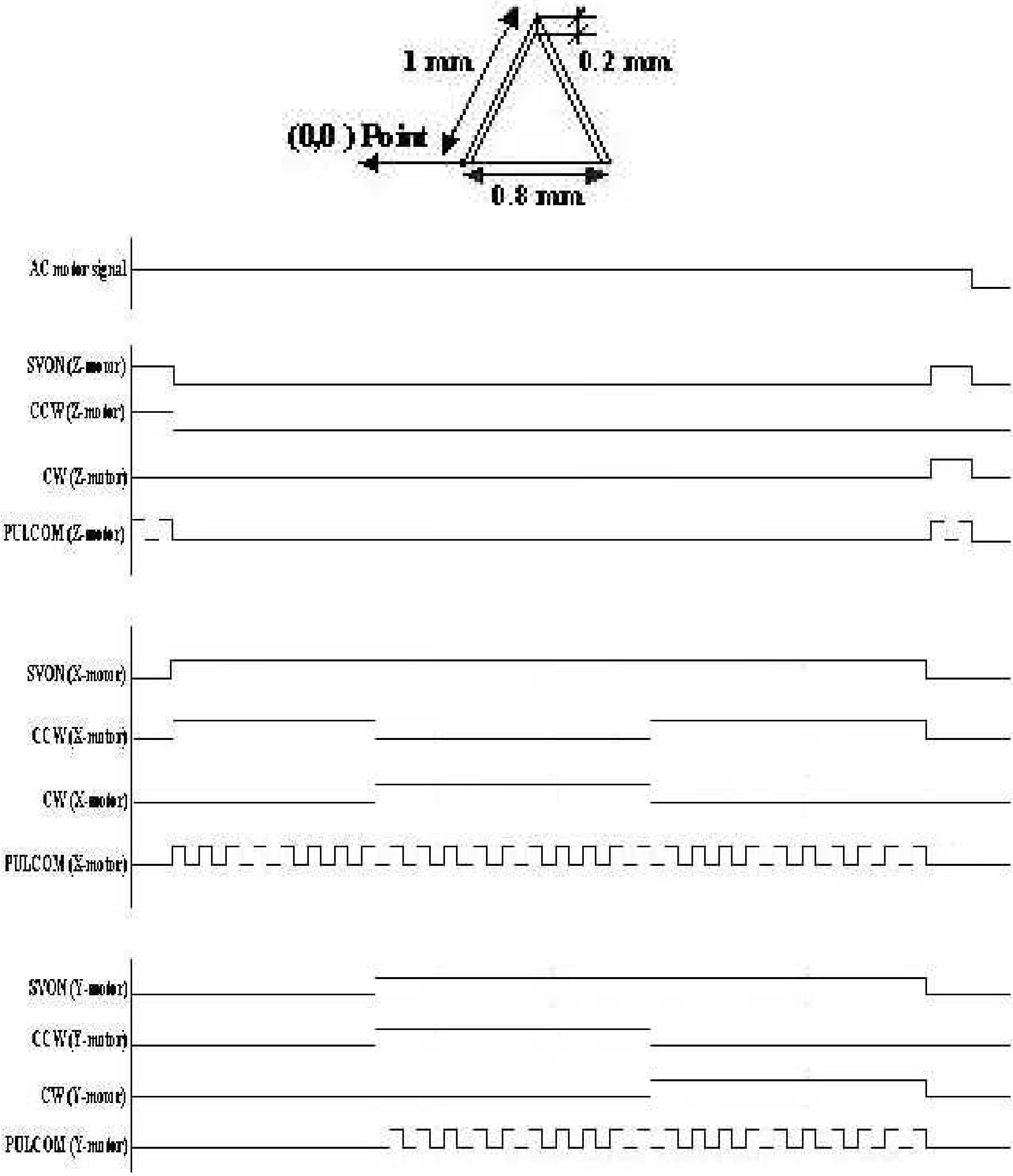



Figure 8.2: motor signals when the machine carving a triangle shape

CW : CW rotating (reverse rotation).

CCW : CCW rotating (forward rotation).

SVON : Servo operating.

PULCOM: Pulse input to control the position of the servo motor..

AC signal: The signal required to operate the AC motor which is used to rotate the cutting part.

We can generate these signals using the simulation program such as (PLC, and Mathlab) as shown in Appendix A.

# Chapter 9
# Conclusions and Recommendations

## 9.1 Conclusions

- The accuracy, the trust and safety, the simplicity, the high range for speed and position control, and performing the work in a relatively short time are the important features of automatic wood carving and decoration machine.

- The fast response, closed loops, No lost steps, and high resolution is the most important features of the AC servo system that make it suitable to perform the machine operations.

- Whenever the mechanical things are decreased the control operations become easier and more accurate.

- Using of the linear bearing in the machine reduce the friction, simplify the motion, and satisfy the equilibrium in the machine.

- Most of Y and X motors torque is due to the viscous damping while in the Z-motor is due to the load weight.

- The advantage of using a computer is that many loops can be controlled or compensated by the same computer through time-sharing. Furthermore, any adjustments of the compensator parameters required, to yield a desired response can be made by changes in software rather than hardware.

- To protect the cutting part from damage the motors speed on the machine must be set accurately.

### 9.2 Recommendations

We recommend the next researchers in this subject to tom doing the following:

- ✓ Continuing the studies of AC servo systems and its modes, and using it in the graduate project as it is considered the most improvement motor.
- ✓ Continuing the studies of the CNC machines, and using there applications.
- ✓ Developing our machine from (2C,L) machine to three dimensions CNC machine.
- ✓ Fixing the wood board of our machine automatically using  a motor instead of the vises.

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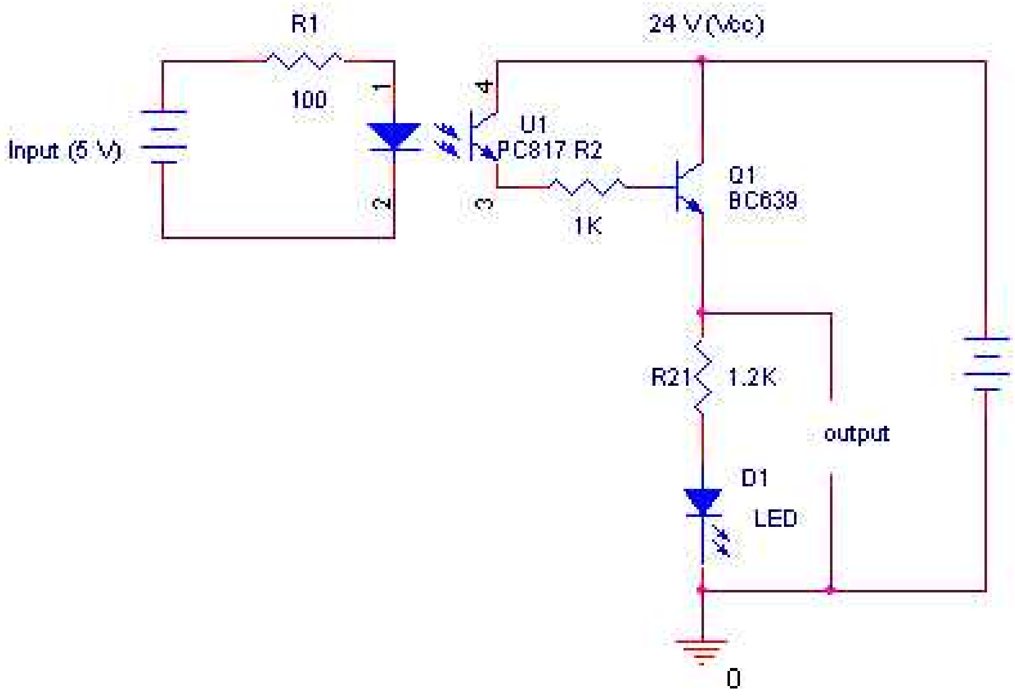
# Appendices

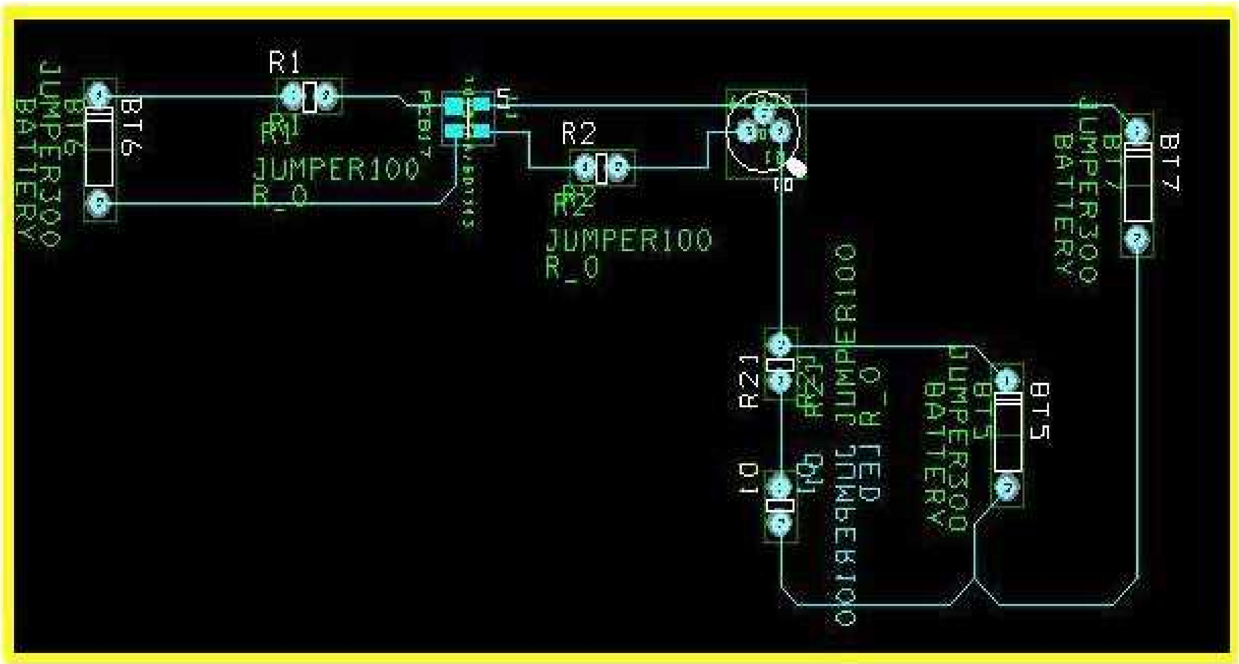
# Appendix A

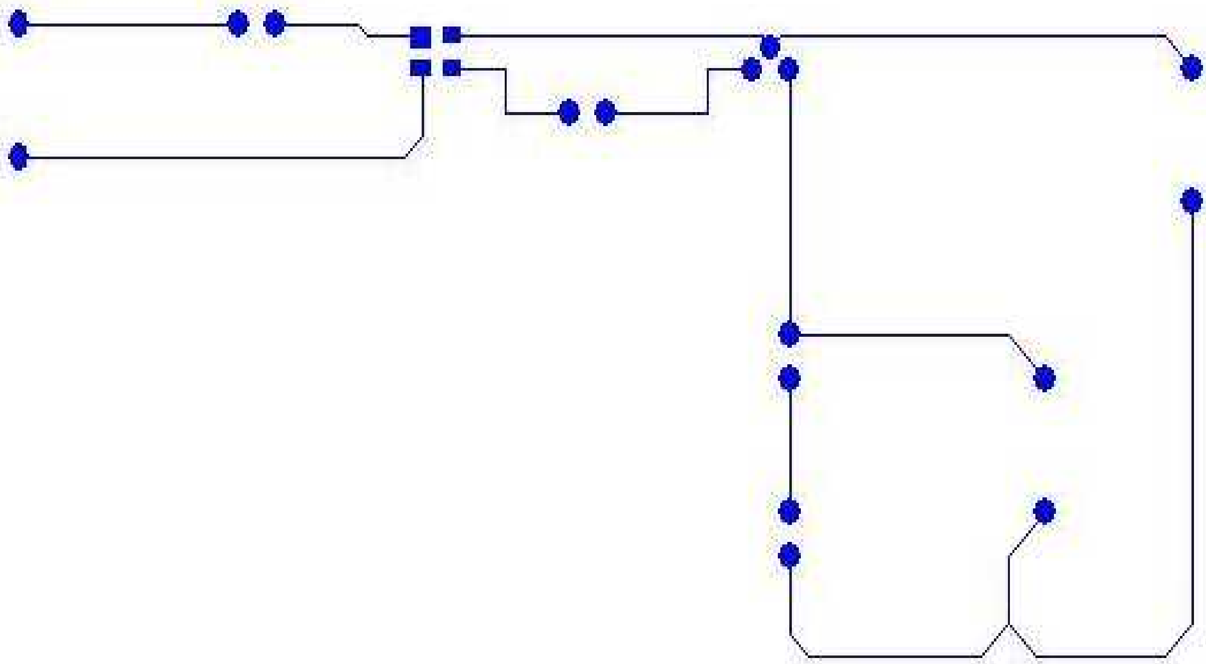
## Simulation Programs

1. Simplorer program.
2. Orcad program.
3. PLC's program.
4. Mathlab program.

**2. The Orcad program which used to make the layout of the machine amplifiers:**



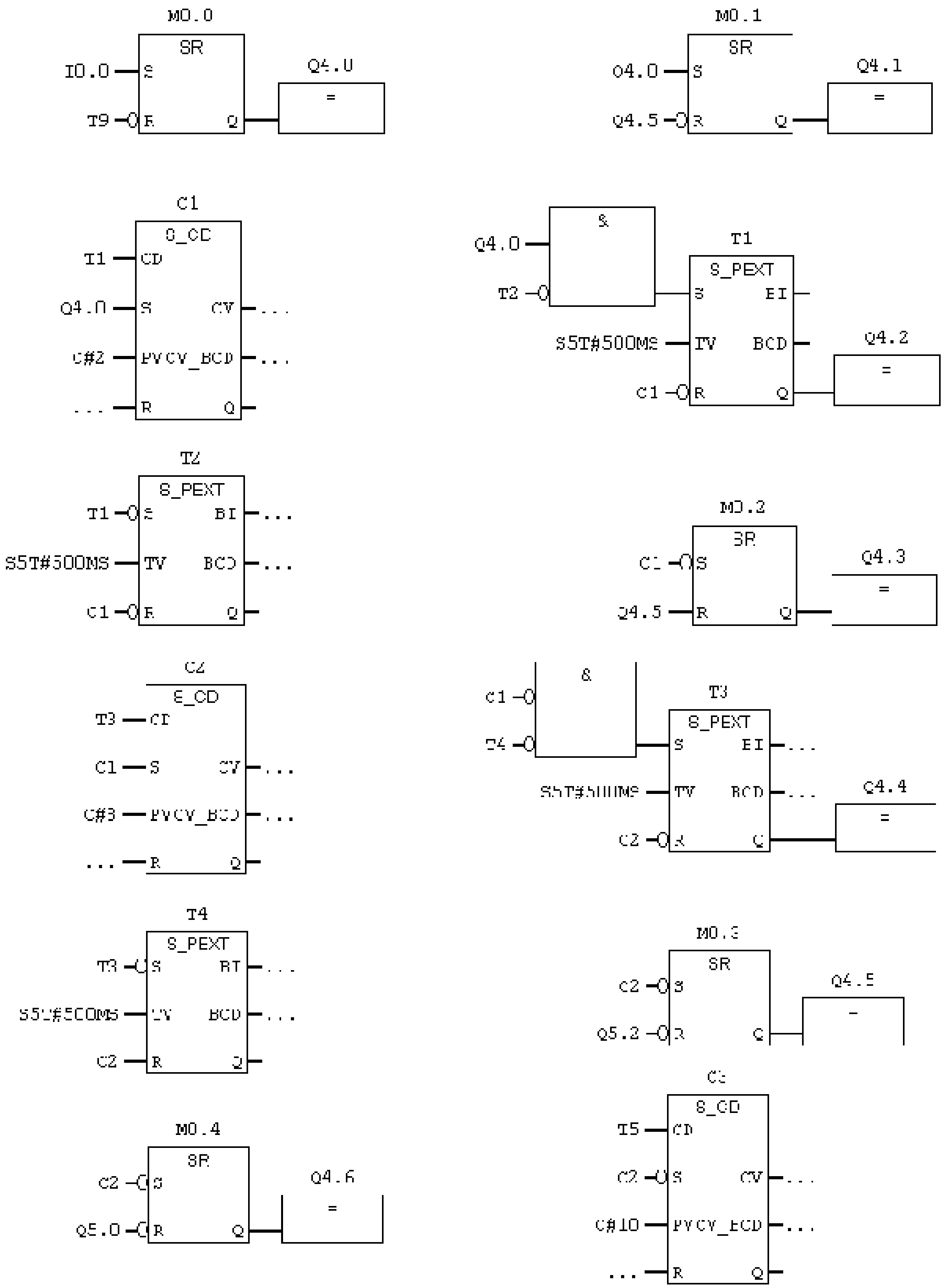


### 3. The PLC program:

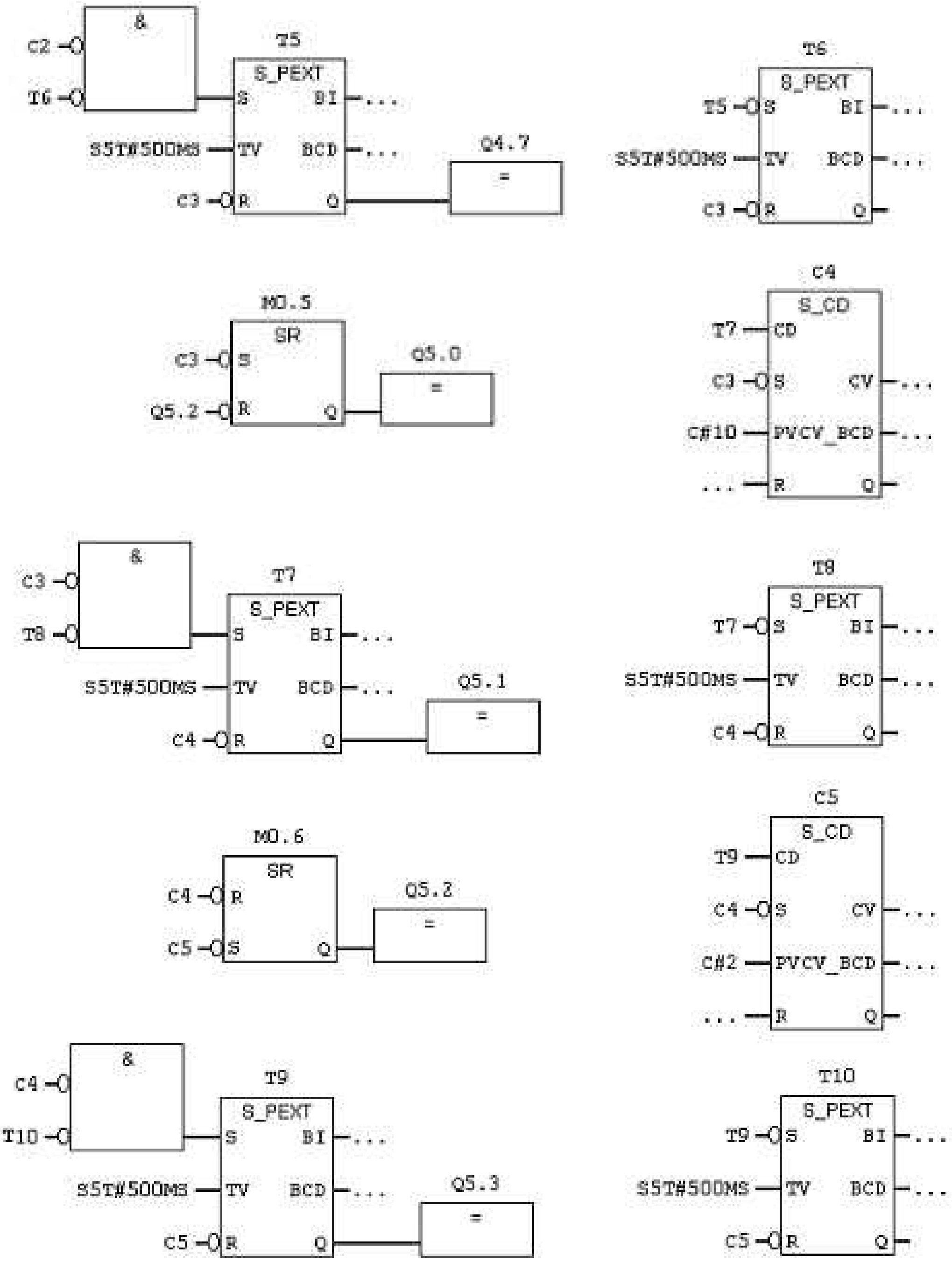
To generate the motor signals to carve the triangle in the results from the PLC the following program is used:

Table (1): Allocation Table

| **Inputs** | **Symbol** | **Logic allocation** |
|---|---|---|
| Operating switch | I0.0 | The machine is operate I0.0 = 1 |
| **Outputs** | **Symbol** | **Logic allocation** |
| AC motor signal | Q4.0 | The AC motor operate Q4.0 = 1 |
| CW (Z) | Q4.1 | Z-motor in the reverse direction Q4.1 = 1 |
| PULSCOM (Z) | Q4.2 | Z-motor spins Q4.2=1 |
| CW (X) | Q4.3 | X-motor in the reverse direction Q4.3 = 1 |
| PULSCOM (X) | Q4.4 | X-motor spins Q4.4 =1 |
| CCW(X) | Q4.5 | X-motor in the forward direction Q4.5 = 1 |
| CCW(Y) | Q4.6 | Y-motor in the forward direction Q4.6 = 1 |
| PULSCOM(X,Y) | Q4.7 | X,Y-motors spin Q4.7=1 |
| CW(Y) | Q5.0 | Y-motor in the reverse direction Q5.0 = 1 |
| PUSCOM(Y,X) | Q5.1 | Y,X -motors spin Q5.1=1 |
| CCW(Z) | Q5.2 | Z-motor in the forward direction Q4.5 = 1 |
| PULSCOM(Z) | Q5.3 | Z-motor spins Q5.3=1 |

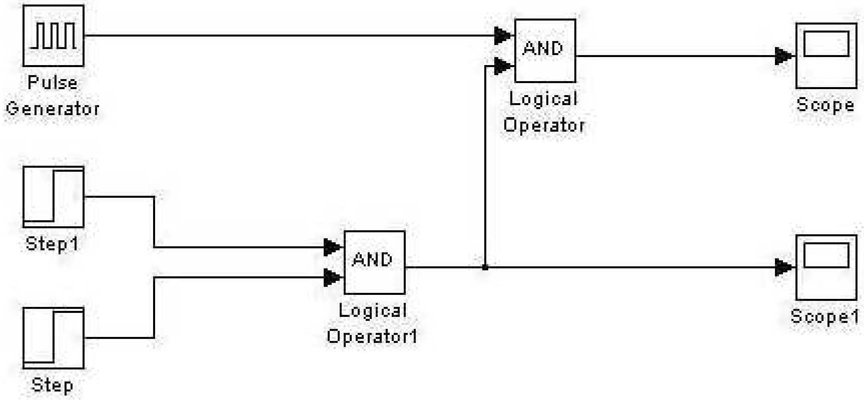


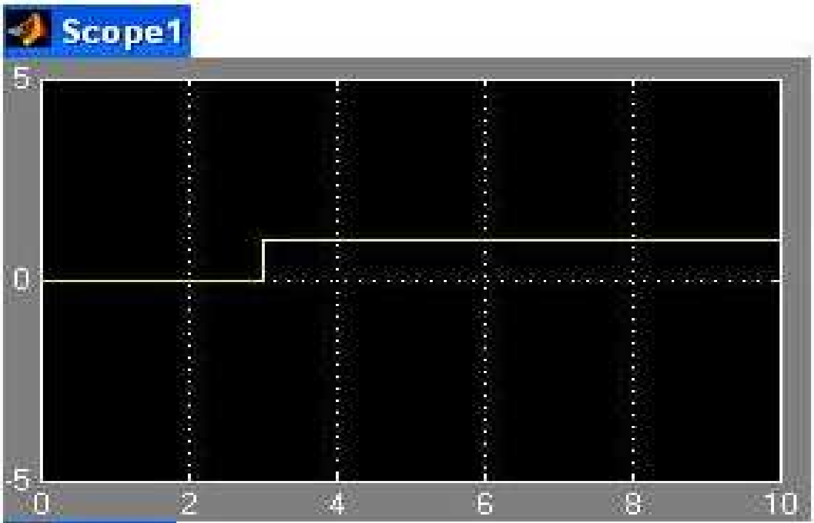
M0.0
SR
I0.0
S
T9
R
Q
Q4.0
=
M0.1
SR
Q4.0
S
Q4.5
R
Q
Q4.1
=
C1
S_CD
T1
CD
Q4.0
S
CV
C#2
PV
CV_BCD
R
Q
&
Q4.0
T2
T1
S_PEXT
S
BI
S5T#500MS
TV
BCD
Q4.2
=
C1
R
Q
T2
S_PEXT
T1
S
BI
S5T#500MS
TV
BCD
C1
R
Q
M0.2
SR
C1
S
Q4.5
R
Q
Q4.3
=
C2
S_CD
T3
CD
C1
S
CV
C#3
PV
CV_BCD
R
Q
&
C1
T4
T3
S_PEXT
S
BI
TV
BCD
Q4.4
=
C2
R
Q
T4
S_PEXT
T3
S
BI
BCD
C2
R
Q
M0.3
SR
C2
S
Q5.2
R
Q
Q4.5
M0.4
SR
C2
S
Q5.0
R
Q
Q4.6
=
S_CD
T5
CD
C2
S
CV
C#10
PV
R
Q

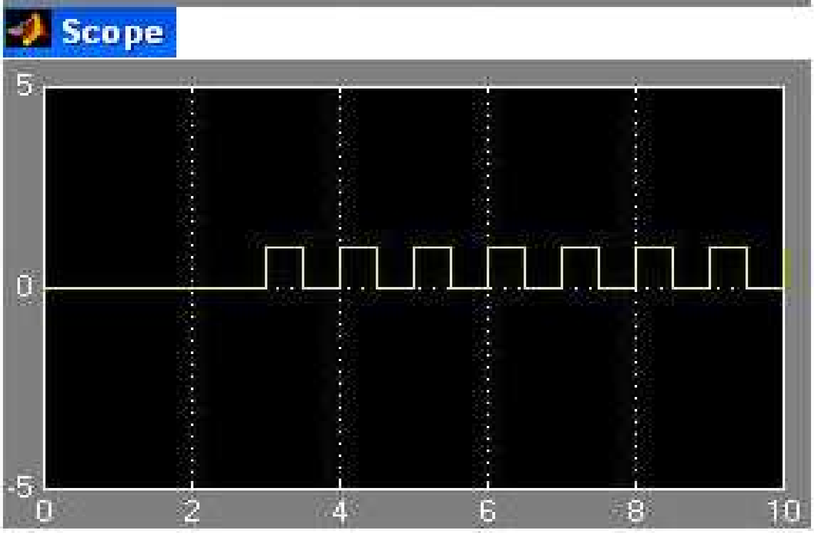

&
C2
T6
T5
S_PEXT
S
BI
S5T#500MS
TV
BCD
C3
R
Q
Q4.7
=
T6
S_PEXT
T5
M0.5
SR
Q5.2
Q5.0
C4
S_CD
T7
CD
CV
C#10
PV
CV_BCD
T7
C4
Q5.1
T8
M0.6
C5
C#2
T9
T10
Q5.3

**4. Mathlab Program:**

We use the Mathlab program to show how we can generate the signals.



# Appendix B

## Data sheets

1. Delta AC servo motor system.
2. PC 817 (Optocoupler).
3. BC 639 (Transistor).
4. Sensors.

DELTA ELECTRONICS, INC.

DELTA AC SERVO SYSTEM

# ASDA-A Series

# User Manual


www.delta.com.tw/industrialautomation

# Chapter 1  Unpacking Check and Model Explanation

## 1.1 Unpacking Check

After receiving the AC servo drive, please check for the following:

- **Ensure that the product is what you have ordered.**

  Verify the part number indicated on the nameplate corresponds with the part number of your order (Please refer to Section 1.2 for details about the model explanation).

- **Ensure that the servo motor shaft rotates freely.**

  Rotate the motor shaft by hand; a smooth rotation will indicate a good motor. However, a servo motor with an electromagnetic brake can not be rotated manually.

- **Check for damage.**

  Inspect the unit to insure it was not damaged during shipment.

- **Check for loose screws.**

  Ensure that all necessary screws are tight and secure.

If any items are damaged or incorrect, please inform the distributor whom you purchased the product from or your local Delta sales representative.

A complete and workable AC servo system should be including the following parts:

Part I : Delta standard supplied parts

(1) Servo drive

(2) Servo motor

(3) 5 PIN Terminal Block (for L1, L2, R, S, T)

(4) 3 PIN Terminal Block (for U, V, W)

(5) 3 PIN Terminal Block (for P, D, C)

(6) One operating lever (for wire to terminal block insertion)

(7) Instruction Sheet

Part II : Optional parts, not Delta standard supplied part (Refer to Appendix A)

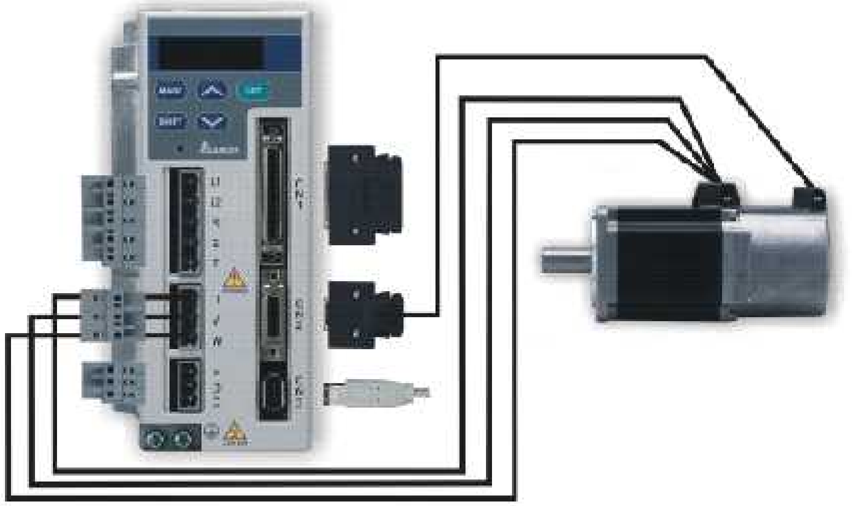
(1) One power cable, which is used to connect servo motor and U, V, W terminals of servo drive. This power cable is with one green grounding cable. Please connect the green grounding cable to the ground terminal of the servo drive.

(2) One encoder cable, which is used to connect the encoder of servo motor and CN2 terminal of servo drive.

(3) CN1 Connector: 50 PIN Connector (3M type analog product)

(4) CN2 Connector: 20 PIN Connector (3M type analog product)

(5) CN3 Connector: 6 PIN Connector (IEEE1394 analog product)



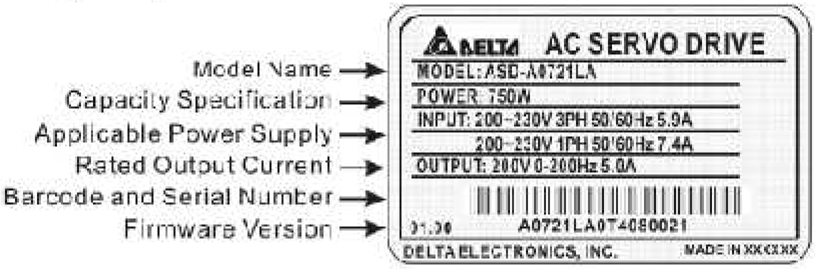
Delta AC Servo Drive and Motor

## 1.2 Model Explanation

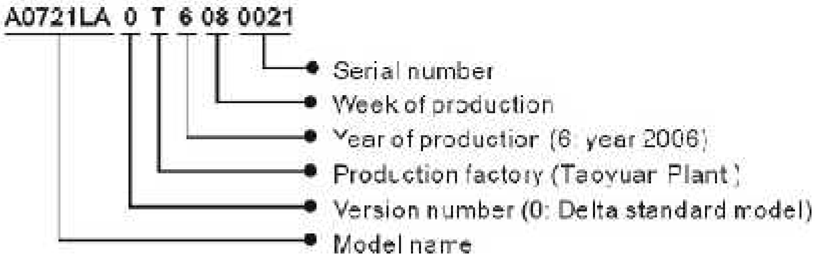
### 1.2.1 Nameplate Information

**ASDA-A Series Servo Drive**

- Nameplate Explanation

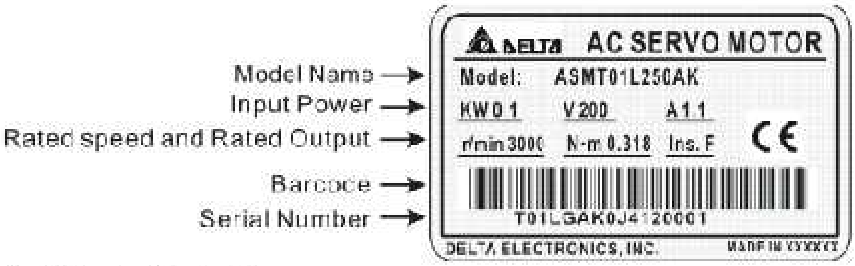



- Serial Number Explanation

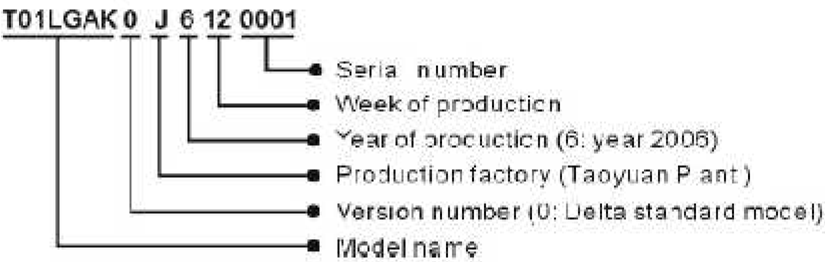



**ASMT Series Servo Motor**

- Nameplate Explanation

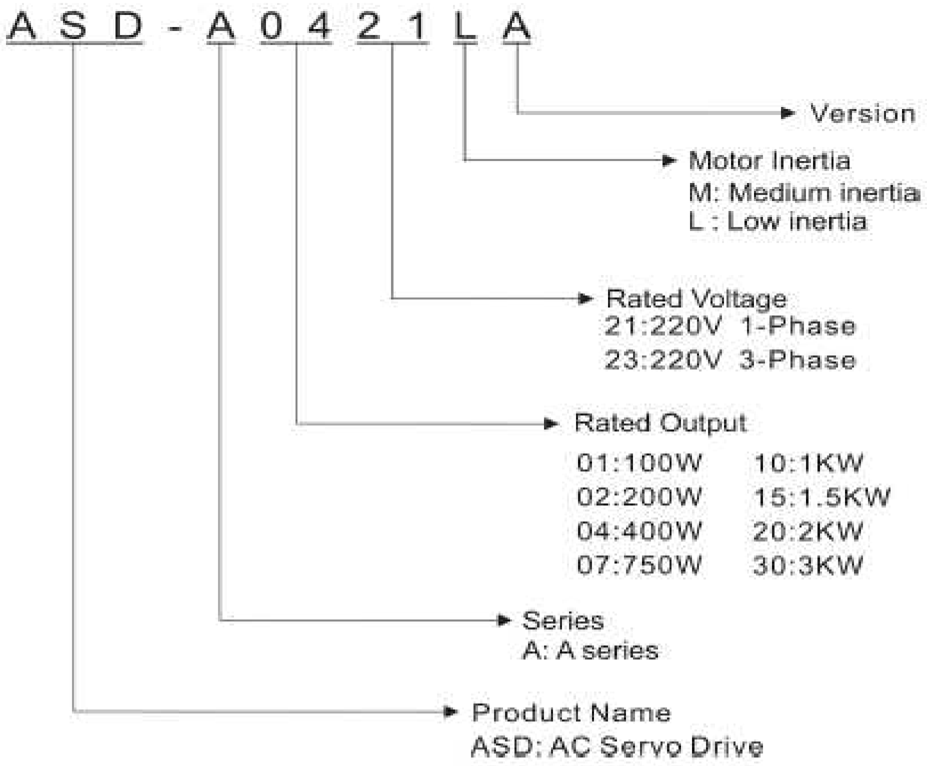



- Serial Number Explanation



### 1.2.2 Model Name Explanation

**ASDA-A Series Servo Drive**



**ASMT Series Servo Motor**

A S M T 0 1 L 2 5 0 A K

| Symbol | Keyway | Oil seal |
|---|---|---|
| K | Y | N |
| O | N | Y |
| M | Y | Y |

Electromagnetic brake
A: Without electromagnetic brake
B: With electromagnetic brake

Encoder Resolution
250: 2500ppr

Motor Inertia
M: Medium inertia
L : Low inertia

Rated Output Power

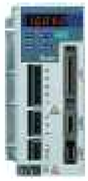
| | |
|---|---|
| 01:100W | 10:1KW |
| 02:200W | 15:1.5KW |
| 04:400W | 20:2KW |
| 07:750W | 30:3KW |

Motor Type
T: T Type

Product Name
ASM: AC Servo Motor

## 1.3 Servo Drive and Servo Motor Combinations

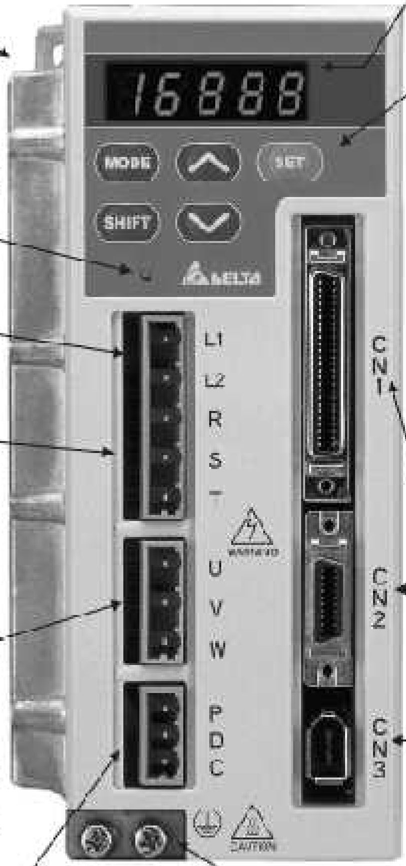
The table below shows the possible combination of Delta ASDA-A series servo drives and ASMT series servo motors. The boxes (□) in the model names are for optional configurations. (Please refer to Section 1.2 for model explanation)

| | | Servo drive | | Servo motor | |
|---|---|---|---|---|---|
| Low inertia | 100W | ASD-A0121L□ |  | ASMT01L250□□ |  |
| | 200W | ASD-A0221L□ | | ASMT02L250□□ |  |
| | 400W | ASD-A0421L□ | | ASMT04L250□□ |  |
| | 750W | ASD-A0721L□ |  | ASMT07L250□□ |  |
| | 1000W | ASD-A1021L□ | | ASMT10L250□□ |  |
| | 2000W | ASD-A2023L□ |  | ASMT20L250□□ |  |
| | 3000W | ASD-A3023L□ | | ASMT30L250□□ |  |

| | | Servo drive | | Servo motor | |
|---|---|---|---|---|---|
| Medium inertia | 1000W | ASD-A1021M□ |  | ASMT10M250□□ |  |
| | 1500W | ASD-A1521M□ | | ASMT15M250□□ |  |
| | 2000W | ASD-A2023M□ |  | ASMT20M250□□ |  |
| | 3000W | ASD-A3023M□ | | ASMT30M250□□ |  |

The drives shown in the above table are designed for use in combination with the specific servo motors. Check the specifications of the drives and motors you want to use.

## 1.4 Servo Drive Features



## 1.5 Control Modes of Servo Drive

The Delta Servo can be programmed to provide six single and five dual modes of operation.

Their operation and description is listed in the following table.

| Mode | | Code | Description |
|---|---|---|---|
| Single Mode | External Position Control | Pt | Position control for the servo motor is achieved via an external pulse command. |
| | Internal Position Control | Pr | Position control for the servo motor is achieved via by 8 commands stored within the servo controller. Execution of the 8 positions is via Digital Input (DI) signals. |
| | Speed Control | S | Speed control for the servo motor can be achieved via parameters set within the controller or from an external analog -10 ~ +10 Vdc command. Control of the internal speed parameters is via the Digital Inputs (DI). (A maximum of three speeds can be stored internally). |
| | Internal Speed Control | Sz | Speed control for the servo motor is only achieved via parameters set within the controller. Control of the internal speed parameters is via the Digital Inputs (DI). (A maximum of three speeds can be stored internally). |
| | Torque Control | T | Torque control for the servo motor can be achieved via parameters set within the controller or from an external analog -10 ~ +10 Vdc command. Control of the internal torque parameters is via the Digital Inputs (DI). (A maximum of three torque levels can be stored internally). |
| | Internal Torque Control | Tz | Torque control for the servo motor is only achieved via parameters set within the controller. Control of the internal torque parameters is via the Digital Inputs (DI). (A maximum of three torque levels can be stored internally). |
| Dual Mode | | Pt-S | Either Pt or S control mode can be selected via the Digital Inputs (DI) |
| | | Pt-T | Either Pt or T control mode can be selected via the Digital Inputs (DI) |
| | | Pr-S | Either Pr or S control mode can be selected via the Digital Inputs (DI) |
| | | Pr-T | Either Pr or T control mode can be selected via the Digital Inputs (DI) |
| | | S-T | Either S or T control mode can be selected via the Digital Inputs (DI) |

The above control modes can be accessed and changed via by parameter P1-01. If the control mode is changed, switch the drive off and on after the new control mode has been entered. The new control mode will only be valid after drive off/on action. Please see safety precautions on page iii (switching drive off/on multiple times).

# Chapter 3 Configuration and Wiring

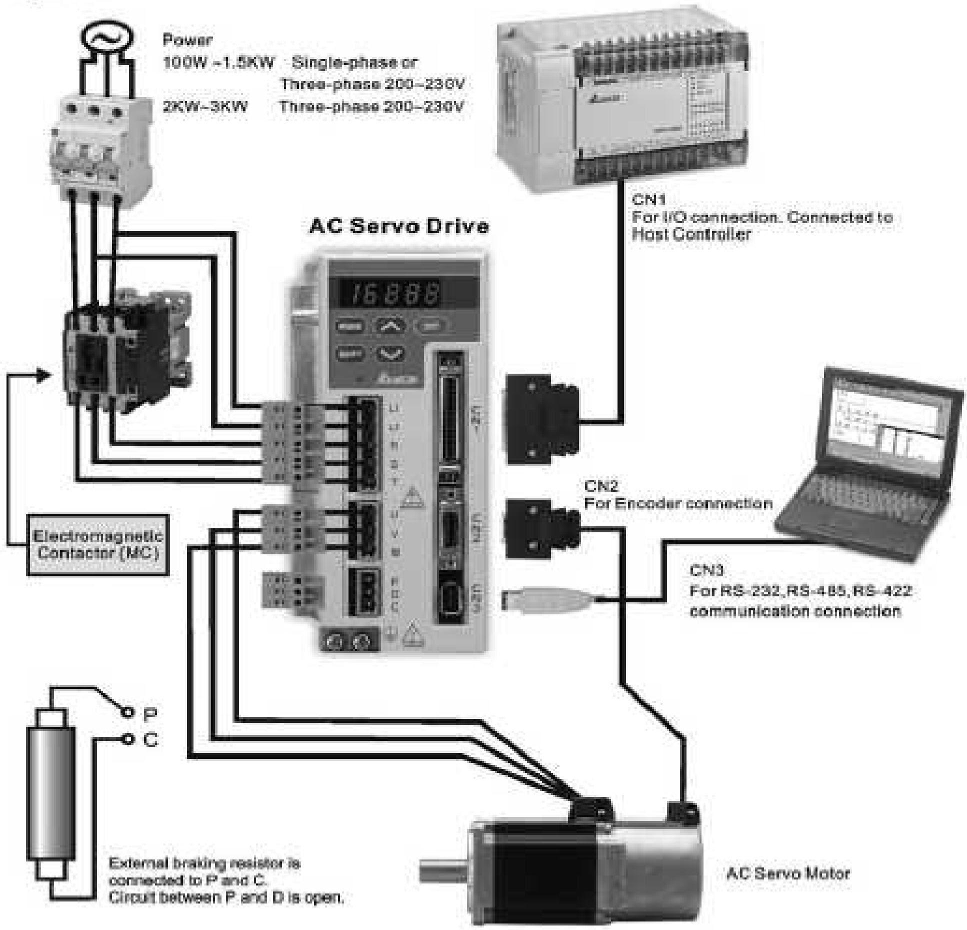
This chapter provides information on wiring ASDA-A series products, the descriptions of I/O signals and gives typical examples of wiring diagrams.

## 3.1 Configuration

### 3.1.1 Connecting to Peripheral Devices

In Figure 3.1, it briefly explains how to connect each peripheral device.

**Figure 3.1**




"When using an external regenerative resistor, ensure P and D is closed, and P and C is open. When using an internal regenerative resistor, connect regenerative resistor to P and C, and ensure an open circuit between P and D."

### 3.1.2 Servo Drive Connectors and Terminals

<table>
<tr><th>Terminal Identification</th><th>Terminal Description</th><th colspan="3">Notes</th></tr>
<tr><td>L1, L2</td><td>Control circuit terminal</td><td colspan="3">The servo Control Circuit requires an independent 220V single-phase VAC supply.</td></tr>
<tr><td>R, S, T</td><td>Main circuit terminal</td><td colspan="3">The Main Circuit Terminal is used to supply the servo with line power. If a single-phase supply, is used connect the R and S terminals to power. If 3-phase, connect all three R, S, & T terminals. To provide Control Circuit power two jumpers can be added from R and S to L1 and L2.</td></tr>
<tr><td rowspan="6">U, V, W<br>FG</td><td rowspan="6">Servo motor output</td><td colspan="3">Used to connect servo motor</td></tr>
<tr><td>Terminal Symbol</td><td>Wire Color</td><td></td></tr>
<tr><td>U</td><td>Red</td><td></td></tr>
<tr><td>V</td><td>White</td><td></td></tr>
<tr><td>W</td><td>Black</td><td></td></tr>
<tr><td>FG</td><td>Green</td><td></td></tr>
<tr><td rowspan="2">P, D, C</td><td rowspan="2">Regenerative resistor terminal</td><td>Internal resistor</td><td colspan="2">Ensure the circuit is closed between P and D, and the circuit is open between P and C.</td></tr>
<tr><td>External resistor</td><td colspan="2">Connect regenerative resistor to P and C, and ensure an open circuit between P and D.</td></tr>
<tr><td>⏚ two places</td><td>Ground terminal</td><td colspan="3">Used to connect grounding wire of power supply and servo motor.</td></tr>
<tr><td>CN1</td><td>I/O connector</td><td colspan="3">Used to connect external controllers. Please refer to section 3.3 for details.</td></tr>
<tr><td rowspan="10">CN2</td><td rowspan="10">Encoder connector</td><td colspan="3">Used to connect encoder of servo motor. Please refer to section 3.4 for details.</td></tr>
<tr><td>Terminal Symbol</td><td>Wire Color</td><td></td></tr>
<tr><td>A</td><td>Blue</td><td></td></tr>
<tr><td>/A</td><td>Blue/Black</td><td></td></tr>
<tr><td>B</td><td>Green</td><td></td></tr>
<tr><td>/B</td><td>Green/Black</td><td></td></tr>
<tr><td>Z</td><td>Yellow</td><td></td></tr>
<tr><td>/Z</td><td>Yellow/Black</td><td></td></tr>
<tr><td>+5V</td><td>Red</td><td></td></tr>
<tr><td>GND</td><td>Black</td><td></td></tr>
<tr><td>CN3</td><td>Communication connector</td><td colspan="3">Used to connect PC or keypad. Please refer to section 3.5 for details.</td></tr>
</table>

**NOTE**

1) U, V ,W , CN1, CN2, CN3 terminals provide short circuit protection.

## 3.2 Basic Wiring

**Figure 3.4 Basic Wiring Schematic of 100W ~ 1.5kW models**

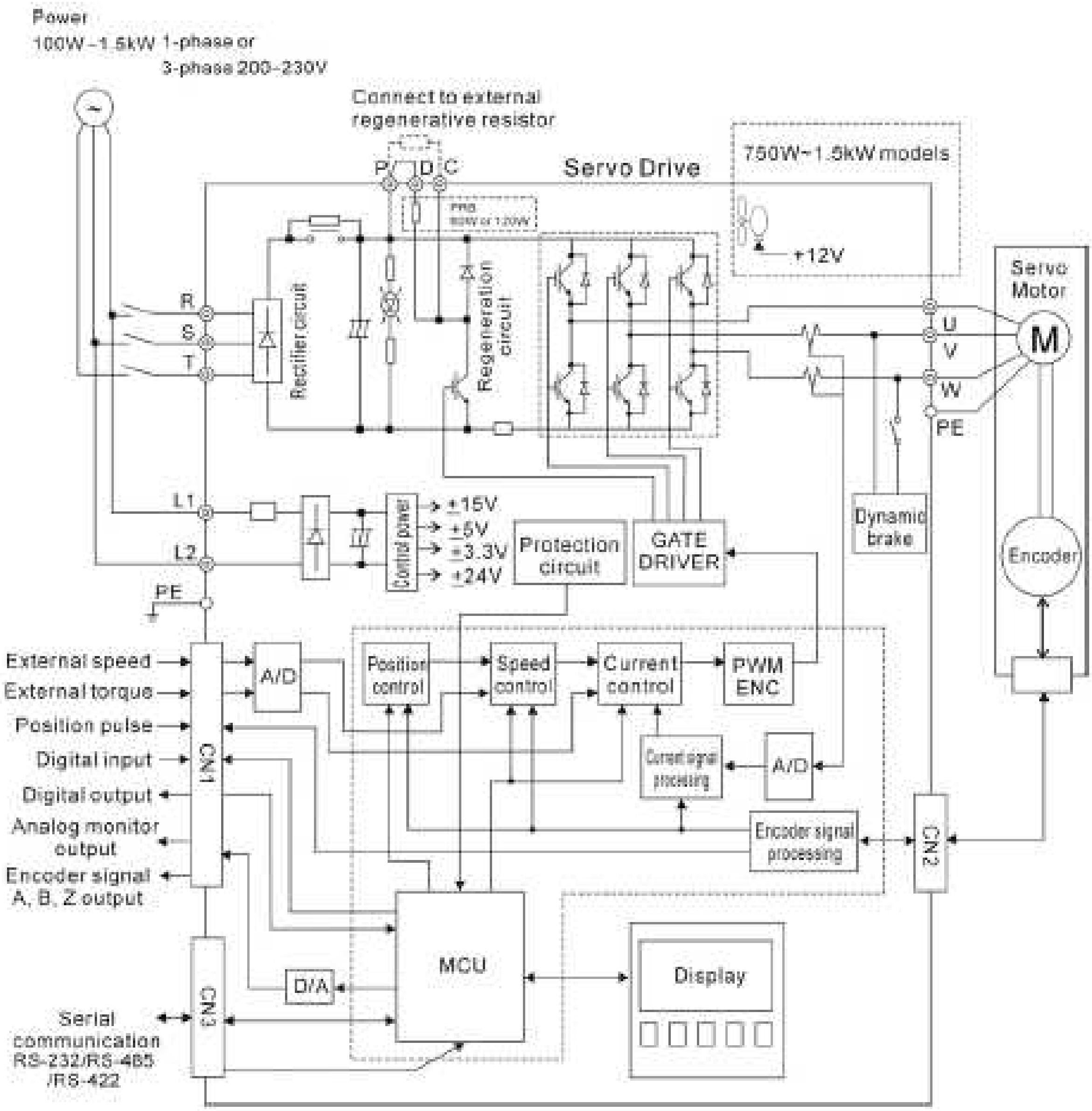
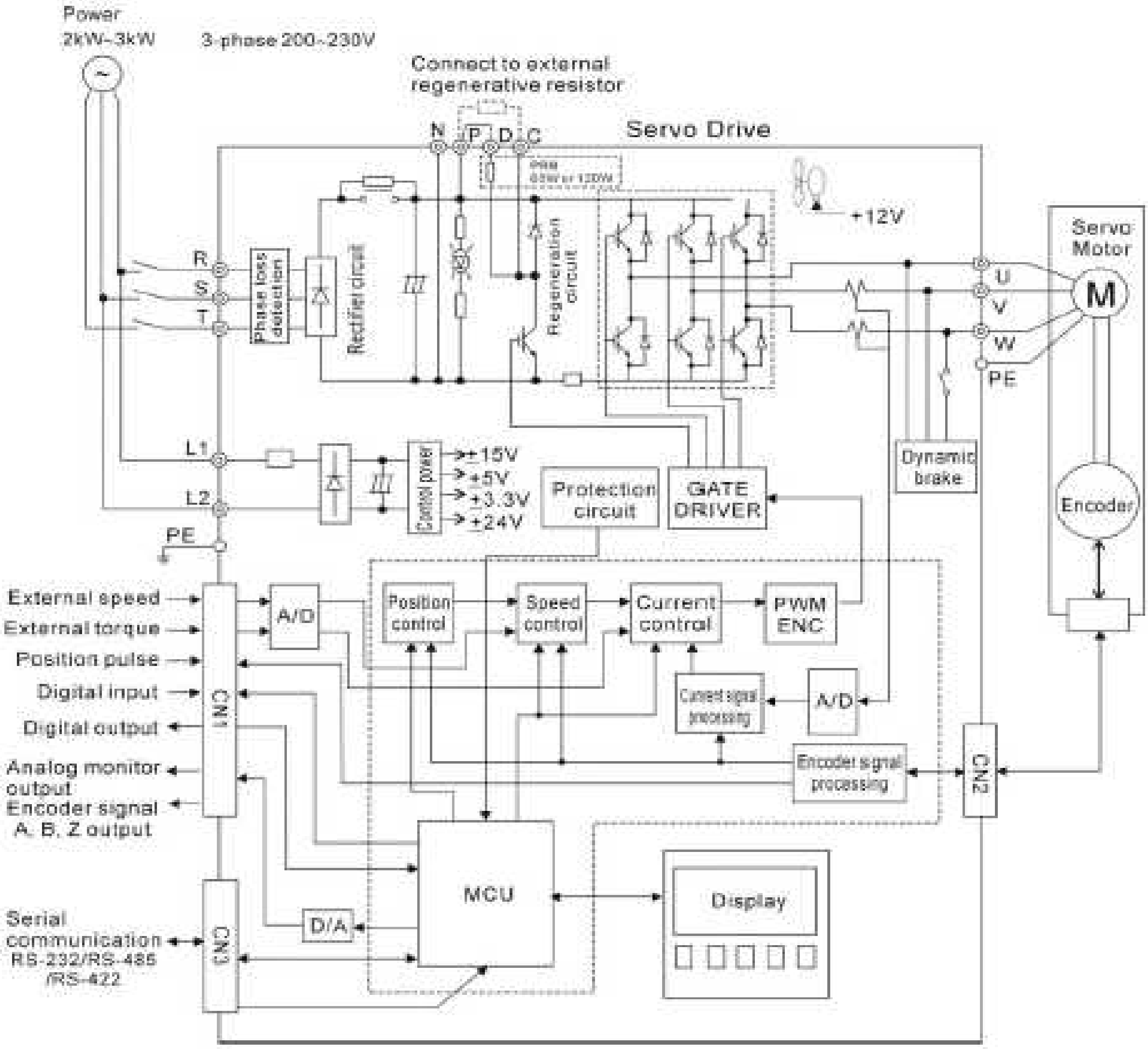


**Figure 3.5 Basic Wiring Schematic of 2kW ~ 3kW models**



### 3.3.2 Signals Explanation of Connector CN1

The Tables 3.A, 3.B, & 3.C detail the three groups of signals of the CN1 interface. Table 3.A details the general signals. Table 3.B details the Digital Output (DO) signals and Table 3.C details the Digital Input (DI) signals. The General Signals are set by the factory and can not be changed, reprogrammed or adjusted. Both the Digital Input and Digital Output signals can be programmed by the users.

**Table 3.A General Signals**

| Signal | | Pin No | Details | Wiring Diagram (Refer to 3-3-3) |
|---|---|---|---|---|
| Analog Signal Input | V_REF | 42 | Motor speed command: -10V to +10V, corresponds to the maximum speed programmed P1-55 Maximum Speed Limit (Factory default 3000 RPM). | C1 |
| | T_REF | 18 | Motor torque command: -10V to +10V, corresponds to -100% to +100% rated torque command. | C1 |
| Analog Monitor Output | MON1<br>MON2 | 16<br>15 | The MON1 and MON2 can be assigned drive and motor parameters that can be monitored via an analogue voltage.<br>Please reference parameter P0-03 for monitoring commands and P1-04 / P1-05 for scaling factors.<br>Output voltage is reference to the power ground. | C2 |
| Position Pulse Input | PULSE<br>/PULSE<br>SIGN<br>/SIGN | 41<br>43<br>37<br>36 | The drive can accept two different types of pulse inputs: Open Collector and Line Driver.<br>Three different pulse commands can be selected via parameter P1-00. Quadrature , CW + CCW pulse & Pulse / Direction. | C3/C4 |
| | PULL HI | 35 | Should an Open Collector type of pulse be used this terminal must be lulled high to pin 17. | C3 |
| Position Pulse Output | OA<br>/OA | 21<br>22 | The motor encoder signals are available through these terminals. The encoder output pulse count can be set via parameter P1-46. | C11/C12 |
| | OB<br>/OB | 25<br>23 | | |
| | OZ<br>/OZ | 50<br>24 | | |
| Power | VDD | 17 | VDD is the +24V source voltage provided by the drive. Maximum permissible current 500mA. | - |
| | COM+<br>COM- | 11<br>45<br>47<br>49 | COM+ is the common voltage rail of the Digital Input and Digital Output signals. Connect VDD to COM+ for source mode. For external applied power sink mode (+12V to +24V), the positive terminal should be connected to COM+ and the negative to COM-. | |
| Power | VCC | 20 | VCC is a +12V power rail provided by the drive. It can be used for the input on an analog speed or torque command. Maximum permissible current 100mA. | - |
| | GND | 12,13,<br>19,44 | The polarity of VCC is with respect to Ground (GND). | |

| Signal | | Pin No | Details | Wiring Diagram (Refer to 3-3-3) |
|---|---|---|---|---|
| Other | NC | 14,29, 38,39, 40,46, 48 | See previous note for NC terminals CN1 connector on page 3-11. | - |

The Digital Input (DI) and Digital Output (DO) have factory default settings which correspond to the various servo drive control modes. (See section 1.5). However, both the DI's and DO's can be programmed independently to meet the requirements of the users.

Detailed in Tables 3.B and 3.C are the DO and DI functions with their corresponding signal name and wiring schematic. The factory default settings of the DI and DO signals are detailed in Table 3.G and 3.H.

All of the DI's and DO's and their corresponding pin numbers are factory set and non-changeable, however, all of the assigned signals and control modes are user changeable. For Example, the factory default setting of DO5 (pins 28/27) can be assigned to DO1 (pins 7/6) and vise versa.

The following Tables 3.B and 3.C detail the functions, applicable operational modes, signal name and relevant wiring schematic of the default DI and DO signals.

**Table 3.B DO Signals**

| DO Signal | DO Code | Assigned Control Mode | Pin No. (Default) | | Details [(1)] | Wiring Diagram (Refer to 3-3-3) |
|---|---|---|---|---|---|---|
| | | | + | - | | |
| SRDY | 01 | ALL | 7 | 6 | SRDY is activated when the servo drive is ready to run. All fault and alarm conditions, if present, have been cleared. | C5/C6/C7/C8 |
| SON | 02 | Not assigned | - | - | SON is activated when control power is applied the servo drive. The drive may or may not be ready to run as a fault / alarm condition may exist.<br>Servo ON (SON) is "ON" with control power applied to the servo drive, there may be a fault condition or not. The servo is not ready to run. Servo ready (SRDY) is "ON" where the servo is ready to run, NO fault / alarm exists. (P2-51 should turn servo ready SRDY off / on) | |
| ZSPD | 03 | ALL | 5 | 4 | ZSPD is activated when the drive senses the motor is equal to or below the Zero Speed Range setting as defined in parameter P1-38.<br>For Example, at factory default ZSPD will be activated when the drive detects the motor rotating at speed at or below 10 rpm. ZSPD will remain activated until the motor speed increases above 10 RPM. | |

| DO Signal | DO Code | Assigned Control Mode | Pin No. (Default) + | Pin No. (Default) - | Details (*1) | Wiring Diagram (Refer to 3-3-3) |
|---|---|---|---|---|---|---|
| TSPD | 04 | ALL | 3 | 2 | TSPD is activated once the drive has detected the motor has reached the Target Rotation Speed setting as defined in parameter P1-39. TSPD will remain activated until the motor speed drops below the Target Rotation Speed. | C5/C6/C7/C8 |
| TPOS | 05 | Pt, Pr, Pt-S, Pt-T, Pr-S, Pr-T | 1 | 26 | 1. When the drive is in Pt mode, TPOS will be activated when the position error is equal and below the setting value of P1-54. 2. When the drive is in Pr mode, TPOS will be activated when the drive detects that the position of the motor is in a -P1-54 to +P1-54 band of the target position. For Example, at factory default TPOS will activate once the motor is in -99 pulses range of the target position, then deactivate after it reaches +99 pulses range of the desired position. | |
| TQL | 06 | Not assigned | - | - | TQL is activated when the drive has detected that the motor has reached the torques limits set by either the parameters P1-12 ~ P1-14 of via an external analog voltage. | |
| ALRM | 07 | ALL | 28 | 27 | ALRM is activated when the drive has detected a fault condition. (However, when Reverse limit error, Forward limit error, Emergency stop, Serial communication error, and Undervoltage these fault occur, WARN is activated first.) | |
| BRKR | 08 | ALL | 1 | 26 | BRKR is activated actuation of motor brake. | |
| HOME | 09 | Pt, Pr | 3 | 2 | HOME is activated when the servo drive has detected that the "HOME" sensor (Digital Input 24) has been detected and the home conditions set in parameters P1-47, P1-50, and P1-51 have been satisfied. | |
| OLW | 10 | ALL | - | - | OLW is activated when the servo drive has detected that the motor has reached the output overload level set by the parameter P1-56. | |
| WARN | 11 | ALL | - | - | Servo warning output. WARN is activated when the drive has detected Reverse limit error, Forward limit error, Emergency stop, Serial communication error, and Undervoltage these fault conditions. | |

**Footnote *1:** The "state" of the output function may be turned ON or OFF as it will be dependant on the settings of P2-18~P2-22.

**NOTE**

1) PINS 3 & 2 can either be TSPD or HOME dependent upon control mode selected.

2) PINS 1 & 26 are different depending on control mode either BRKR or TPOS.

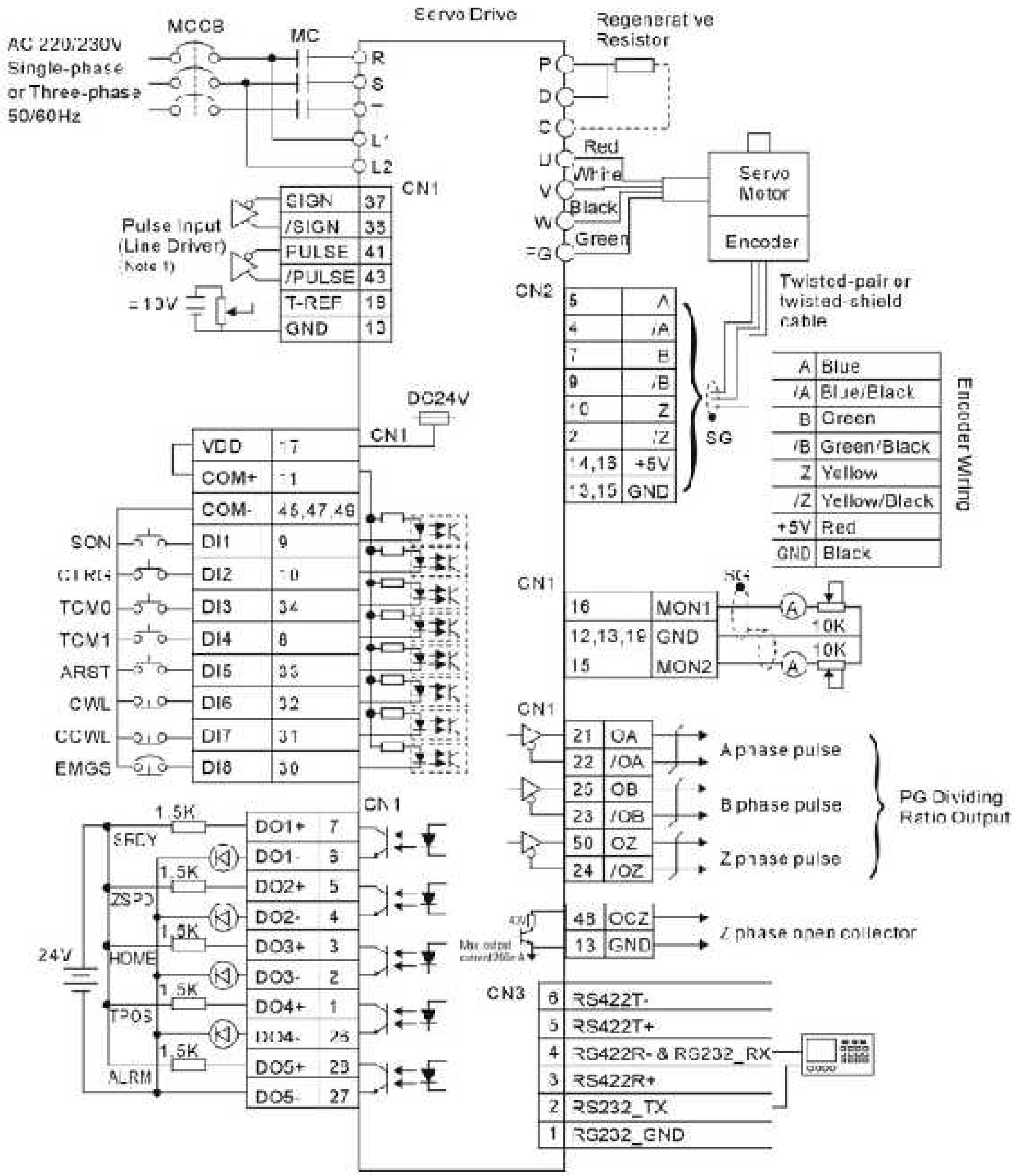
Table 3.C DI Signals

| DI Signal | DI Code | Assigned Control Mode | Pin No. (Default) | Details [*2] | Wiring Diagram (Refer to 3-3-3) |
|---|---|---|---|---|---|
| SON | 01 | ALL | 9 | Servo On. Switch servo to "Servo Ready". Check parameter P2-51. | C9/C10 |
| ARST | 02 | ALL | 33 | A number of Faults (Alarms) can be cleared by activating ARST. Please see table 10-3 for applicable faults that can be cleared with the ARST command. However, please investigate Fault or Alarm if it does not clear or the fault description warrants closer inspection of the drive system. | |
| GAINUP | 03 | ALL | - | Gain switching | |
| CCLR | 04 | Pt | 10 | When CCLR is activated the setting is parameter P2-50 Pulse Clear Mode is executed. | |
| ZCLAMP | 05 | ALL | - | When this signal is On and the motor speed value is lower than the setting value of P1-38, it is used to lock the motor in the instant position while ZCLAMP is On. | |
| CMDINV | 06 | Pr, T, S | - | When this signal is On, the motor is in reverse rotation. | |
| HOLD | 07 | Not assigned | | Internal position control command pause | |
| CTRG | 08 | Pr, Pr-S, Pr-T | 10 | When the drive is in Pr mode and CTRG is activated, the drive will command the motor to move the stored position which correspond the POS 0, POS 1, POS 2 settings. Activation is triggered on the rising edge of the pulse. | |
| TRQLM | 09 | S, Sz | 10 | ON indicates the torque limit command is valid. | |
| SPDLM | 10 | T, Tz | 10 | ON indicates the speed limit command is valid. | |
| POS0 | 11 | Pr | 34 | When the Pr Control Mode is selected the 8 stored positions are programmed via a combination of the POS 0, POS 1, and POS 2 commands. See table 3.D. | |
| POS1 | 12 | Pr-S, Pr-T | 8 | | |
| POS2 | 13 | - | - | | |
| SPD0 | 14 | S, Sz, Pt-S, Pr-S, S-T | 34 | Select the source of speed command: See table 3.E. | |
| SPD1 | 15 | | 8 | | |
| TCM0 | 16 | Pt, T, Tz, Pt-T, Pr-T, S-T | 34 | Select the source of torque command: See table 3.F. | |
| TCM1 | 17 | | 8 | | |
| S-P | 18 | Pt-S, Pr-S | 31 | Speed / Position mode switching<br>OFF: Speed, ON: Position | |
| S-T | 19 | S-T | 31 | Speed / Torque mode switching<br>OFF: Speed, ON: Torque | |

| DI Signal | DI Code | Assigned Control Mode | Pin No. (Default) | Details (*2) | Wiring Diagram (Refer to 3-3-3) |
|---|---|---|---|---|---|
| T-P | 20 | Pt-T, Pr-T | 31 | Torque / Position mode switching<br>OFF: Torque, ON: Position | C9/C10 |
| EMGS | 21 | ALL | 30 | It should be contact "b" and normally ON or a fault (ALE13) will display. | |
| CWL | 22 | Pt, Pr, S, T Sz, Tz | 32 | Reverse inhibit limit. It should be contact "b" and normally ON or a fault (ALE14) will display. | |
| CCWL | 23 | Pt, Pr, S, T Sz, Tz | 31 | Forward inhibit limit. It should be contact "b" and normally ON or a fault (ALE15) will display. | |
| ORGP | 24 | Not assigned | - | When ORGP is activated, the drive will command the motor to start to search the reference "Home" sensor. | |
| TLLM | 25 | Not assigned | - | Reverse operation torque limit (Torque limit function is valid only when P1-02 is enabled) | |
| TRLM | 26 | Not assigned | - | Forward operation torque limit (Torque limit function is valid only when P1-02 is enabled) | |
| SHOM | 27 | Not assigned | - | When SHOM is activated, the drive will command the motor to move to "Home". | |
| INDEX0 | 28 | Not assigned | - | Feed step selection input 0 (bit 0) | |
| INDEX1 | 29 | Not assigned | - | Feed step selection input 1 (bit 1) | |
| INDEX2 | 30 | Not assigned | - | Feed step selection input 2 (bit 2) | |
| INDEX3 | 31 | Not assigned | - | Feed step selection input 3 (bit 3) | |
| INDEX4 | 32 | Not assigned | - | Feed step selection input 4 (bit 4) | |
| MD0 | 33 | Not assigned | - | Feed step mode input 0 (bit 0) | |
| MD1 | 34 | Not assigned | - | Feed step mode input 1 (bit 1) | |
| MDP0 | 35 | Not assigned | - | Manually continuous operation | |
| MDP1 | 36 | Not assigned | - | Manually single step operation | |
| JOGU | 37 | Not assigned | - | Forward JOG input. When JOGU is activated, the motor will JOG in forward direction. [see P4-05] | |
| JOGD | 38 | Not assigned | - | Reverse JOG input. When JOGD is activated, the motor will JOG in reverse direction. [see P4-05] | |
| STEPU | 39 | Not assigned | - | Step up input. When STEPU is activated, the motor will run to next position. | |

## 3.6 Standard Connection Example

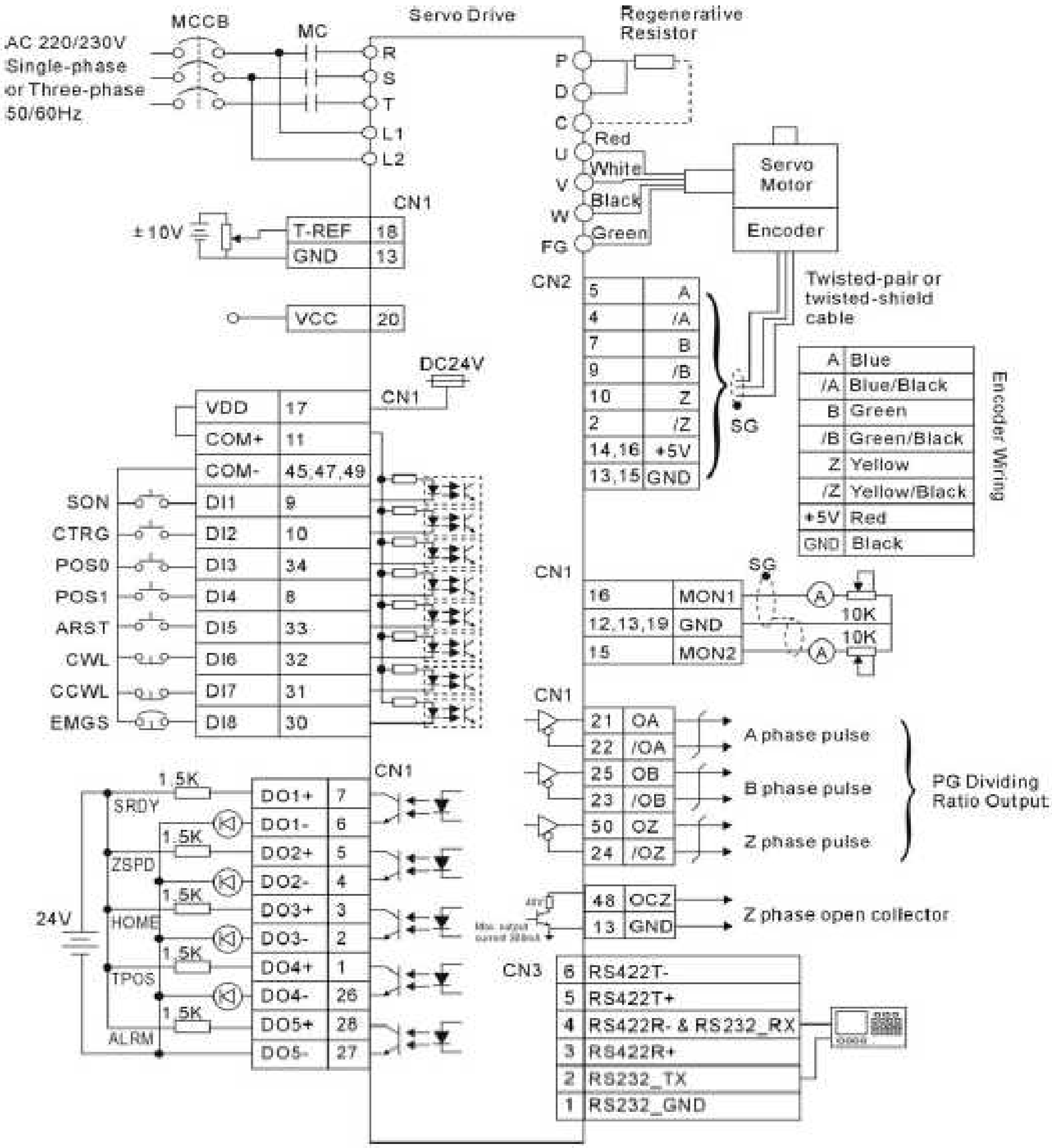
### 3.6.1 Position (Pt) Control Mode



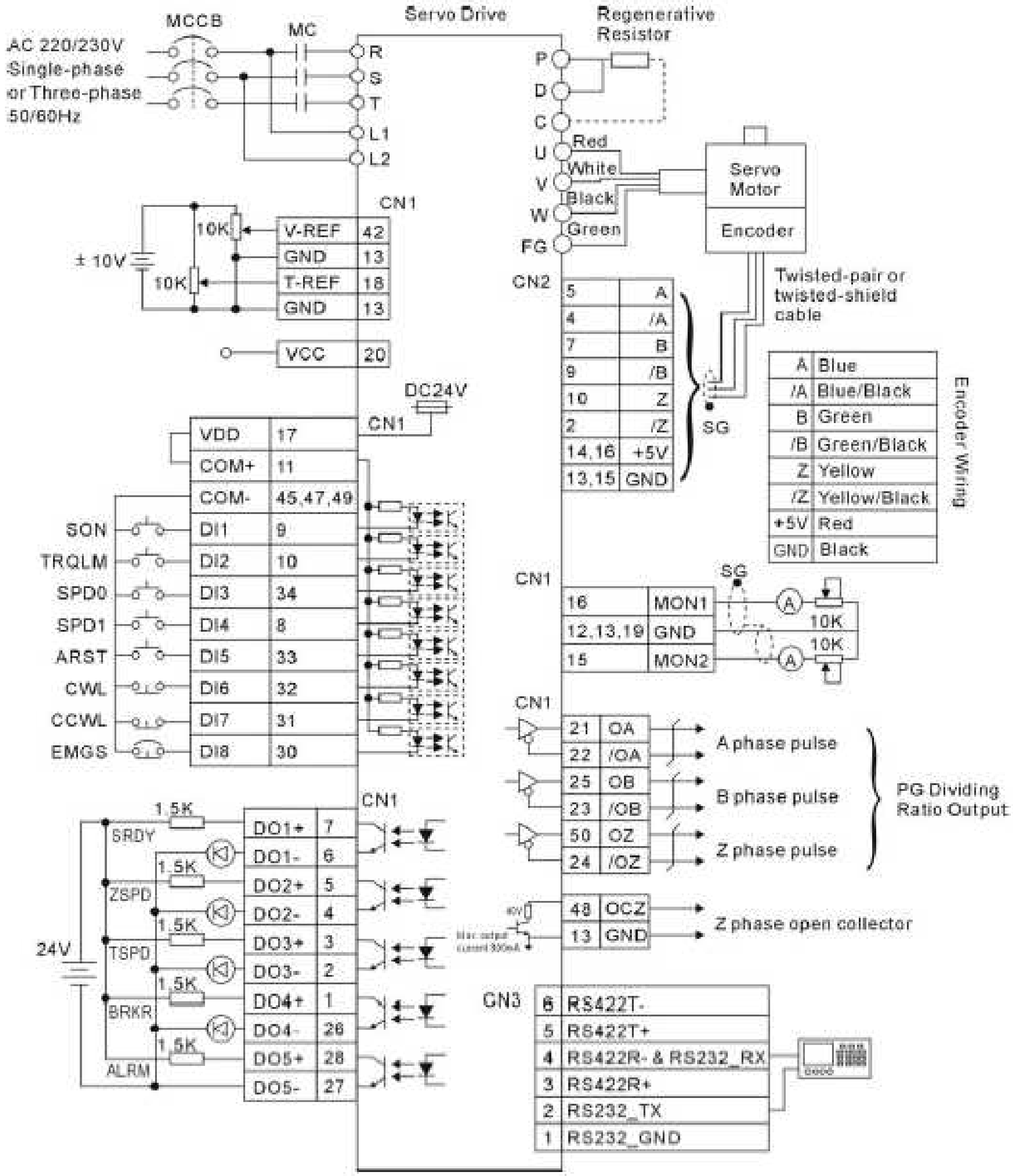

**NOTE**

1) Please refer to C4 wiring diagram on page 3-26. If it is open-collector input, please refer to C3 wiring diagram on page 3-26.

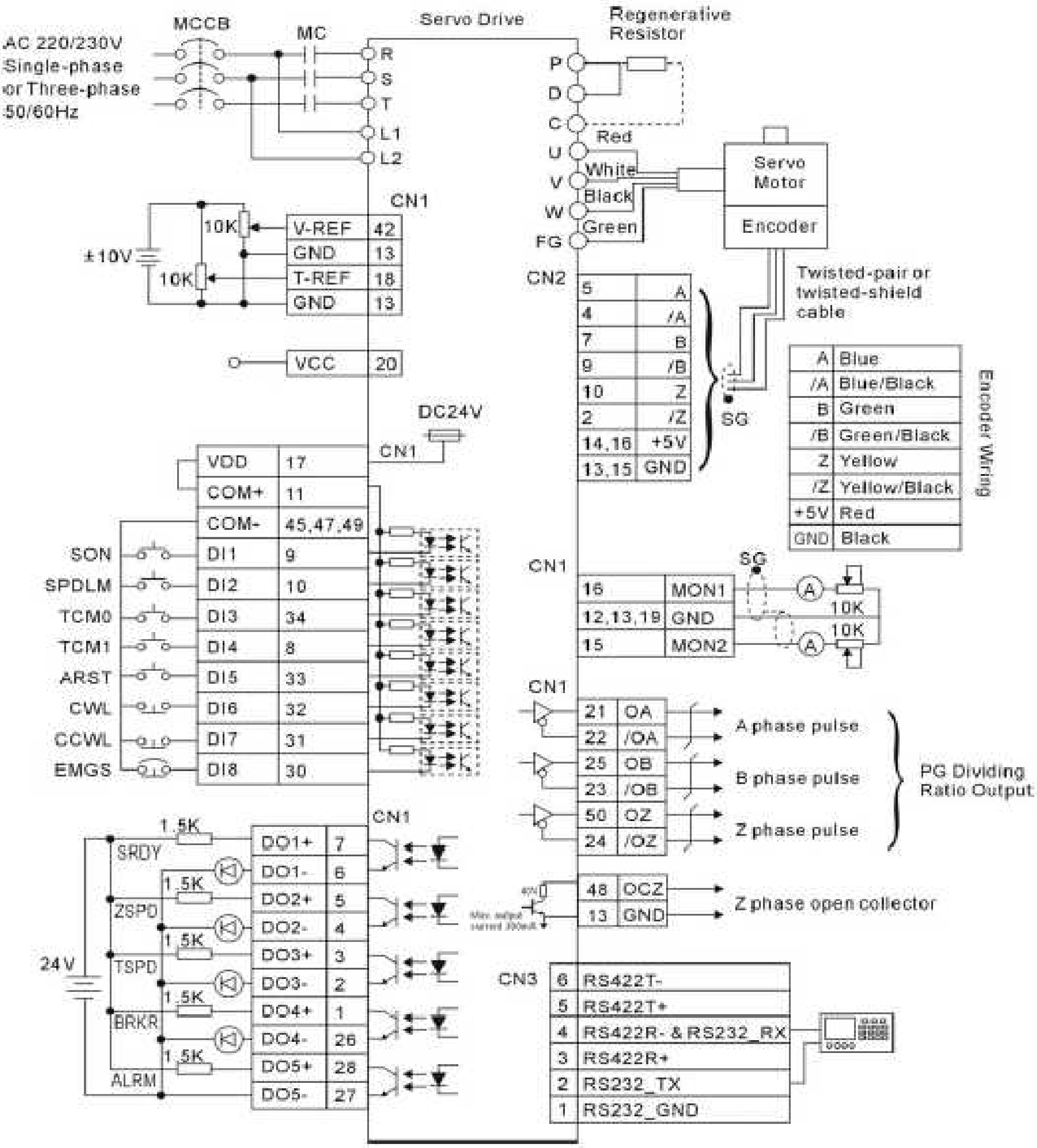
### 3.6.2 Position (Pr) Control Mode



### 3.6.3 Speed Control Mode



### 3.6.4 Torque Control Mode

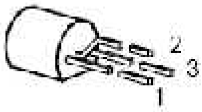


**SIEMENS**

## NPN Silicon AF Transistors

**BC 635**
**... BC 639**

- High current gain
- High collector current
- Low collector-emitter saturation voltage
- Complementary types: BC 636, BC 638, BC 640 (PNP)




| Type | Marking | Ordering Code | Pin Configuration 1 | 2 | 3 | Package[1)] |
|---|---|---|---|---|---|---|
| BC 635<br>BC 637<br>BC 639 | – | Q68000-A3360<br>Q68000-A2285<br>Q68000-A3361 | E | C | B | TO-92 |

If desired, selected transistors, type BC 63 ★ –10 ($h_{FE}$ = 63 ... 160), or BC 63 ★ –16 ($h_{FE}$ = 100 ... 250) are available. Ordering codes upon request.

1) For detailed information see chapter Package Outlines.

## Maximum Ratings

| Parameter | Symbol | Values BC 635 | BC 637 | BC 639 | Unit |
|---|---|---|---|---|---|
| Collector-emitter voltage | $V_{CEO}$ | 45 | 60 | 80 | V |
| Collector-base voltage | $V_{CBO}$ | 45 | 60 | 100 | |
| Emitter-base voltage | $V_{EBO}$ | 5 | | | |
| Collector current | $I_C$ | 1 | | | A |
| Peak collector current | $I_{CM}$ | 1.5 | | | |
| Base current | $I_B$ | 100 | | | mA |
| Peak base current | $I_{BM}$ | 200 | | | |
| Total power dissipation, $T_C$ = 90 °C[1] | $P_{tot}$ | 0.8 (1) | | | W |
| Junction temperature | $T_j$ | 150 | | | °C |
| Storage temperature range | $T_{stg}$ | – 65 ... + 150 | | | |

## Thermal Resistance

| | | | |
|---|---|---|---|
| Junction - ambient[1] | $R_{th\,JA}$ | $\leq$ 156 | K/W |
| Junction - case[2] | $R_{th\,JC}$ | $\leq$ 75 | |

1) If the transistors with max. 4 mm lead length are fixed on PCBs with a min. 10 mm × 10 mm large copper area for the collector terminal, $R_{th\,JA}$ = 125 K/W and thus $P_{tot\,max}$ = 1 W at $T_A$ = 25 °C.

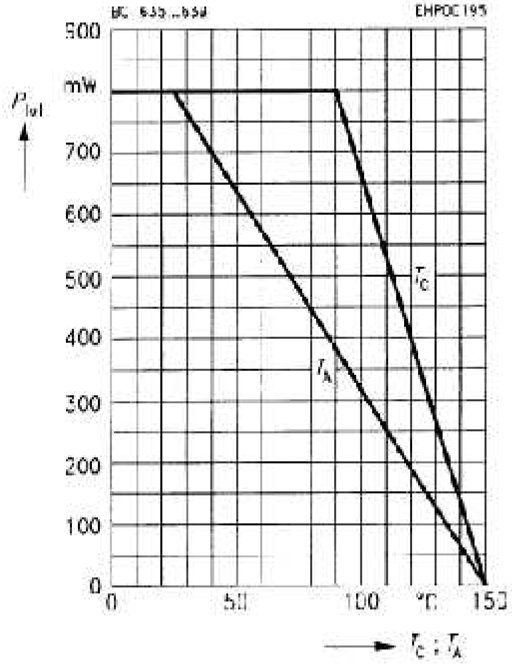
2) Mounted on Al heat sink 15 mm × 25 mm × 0.5 mm.

## Electrical Characteristics

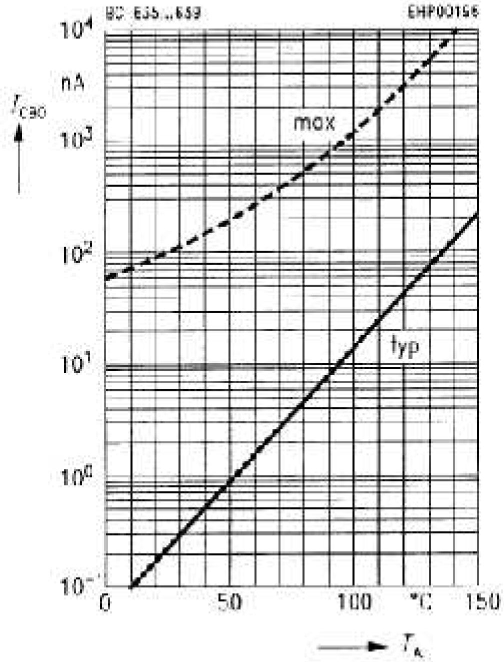
at $T_A$ = 25 °C, unless otherwise specified.

| Parameter | Symbol | Values | | | Unit |
|---|---|---|---|---|---|
| | | min. | typ. | max. | |
| **DC characteristics** | | | | | |
| Collector-emitter breakdown voltage<br>$I_C$ = 10 mA | $V_{(BR)CEO}$ | | | | V |
| BC 635 | | 45 | – | – | |
| BC 637 | | 60 | – | – | |
| BC 639 | | 80 | – | – | |
| Collector-base breakdown voltage<br>$I_C$ = 100 µA | $V_{(BR)CE0}$ | | | | |
| BC 635 | | 45 | – | – | |
| BC 637 | | 60 | – | – | |
| BC 639 | | 100 | | | |
| Emitter-base breakdown voltage<br>$I_E$ = 10 µA | $V_{(BR)EB0}$ | 5 | – | – | |
| Collector cutoff current | $I_{CB0}$ | | | | |
| $V_{CB}$ = 30 V | | – | – | 100 | nA |
| $V_{CB}$ = 30 V, $T_A$ = 150 °C | | – | – | 20 | µA |
| Emitter cutoff current<br>$V_{EB}$ = 4 V | $I_{EB0}$ | – | – | 100 | nA |
| DC current gain | $h_{FE}$ | | | | – |
| $I_C$ = 5 mA; $V_{CE}$ = 2 V | | 25 | – | – | |
| $I_C$ = 150 mA; $V_{CE}$ = 2 V[1)] | | 40 | – | 250 | |
| $I_C$ = 500 mA; $V_{CE}$ = 2 V[1)] | | 25 | – | – | |
| Collector-emitter saturation voltage[1)]<br>$I_C$ = 500 mA; $I_B$ = 50 mA | $V_{CEsat}$ | – | – | 500 | mV |
| Base-emitter voltage[1)]<br>$I_C$ = 500 mA; $V_{CE}$ = 2 V | $V_{BE)}$ | – | – | 1 | V |
| **AC characteristics** | | | | | |
| Transition frequency<br>$I_C$ = 50 mA, $V_{CE}$ = 10 V, $f$ = 20 MHz | $f_T$ | – | 100 | – | MHz |

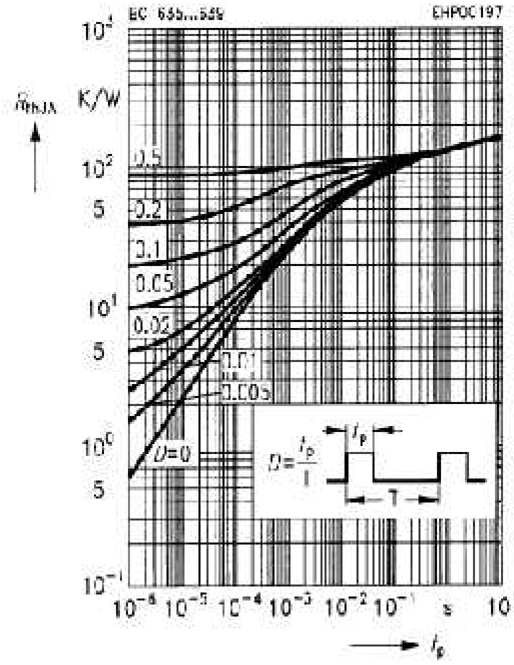
**Total power dissipation** $P_{tot} = f(T_A; T_C)$



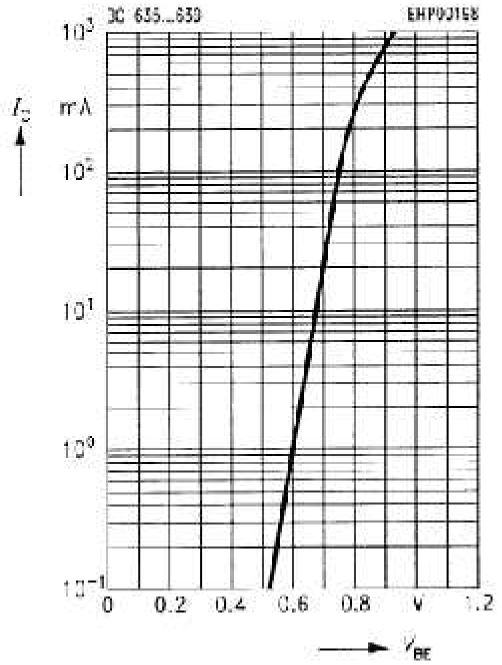

**Collector cutoff current** $I_{CBO} = f(T_A)$
$V_{CB}$ = 30 V



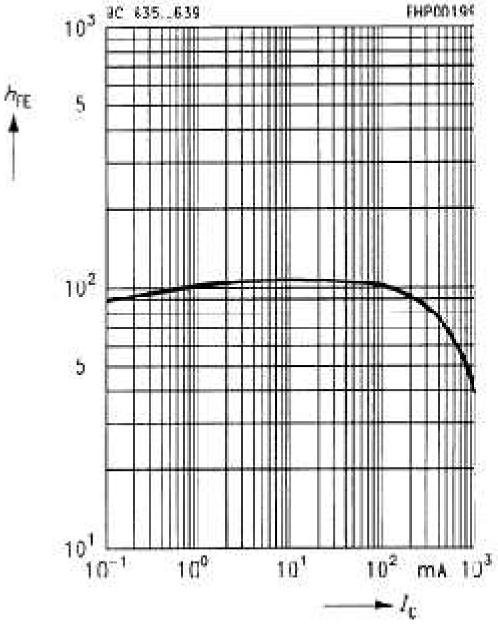

**Permissible pulse load** $R_{thJA} = f(t_p)$
$V_{CE}$ = 2 V



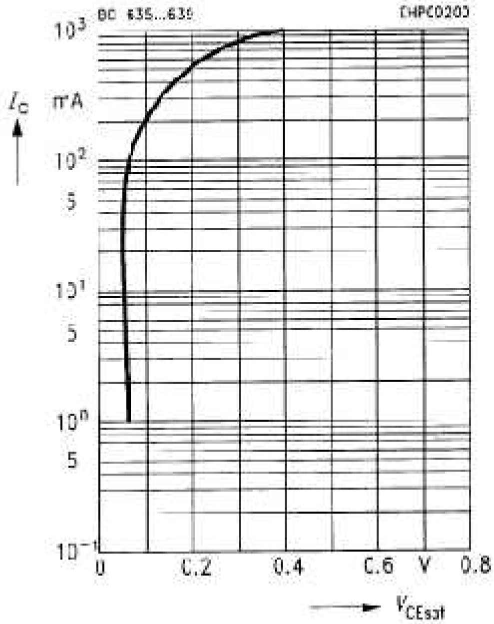

**Collector current** $I_C = f(V_{BE})$



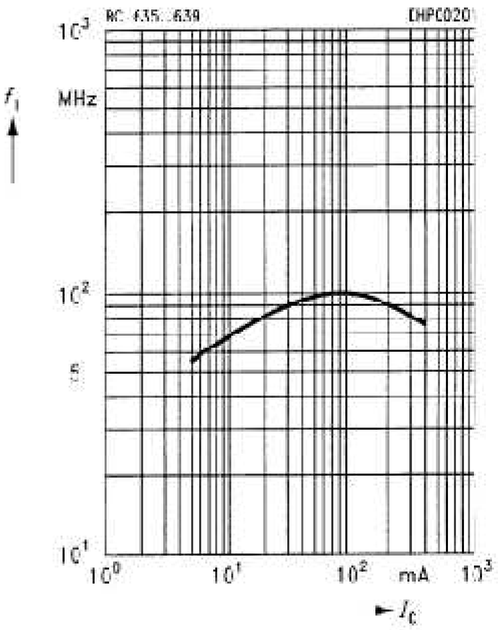
**DC current gain** $h_{FE} = f(I_C)$
$V_{CE}$ = 2 V




**Collector-emitter saturation voltage**
$V_{CEsat} = f(I_C)$
$h_{FE}$ = 10




**Transition frequency** $f_T = f(I_C)$
$V_{CE}$ = 10 V, $f$ = 20 MHz



FAIRCHILD SEMICONDUCTOR®

July 2006

# H11AA814 Series, H11A617 Series, H11A817 Series 4-Pin Phototransistor Optocouplers

## Features

- AC input response (H11AA814 only)
- Compatible to Pb-free IR reflow soldering
- Compact 4-pin dual in-line package
- Current transfer ratio in selected groups:

| | | | |
|---|---|---|---|
| H11AA814: | 20-300% | H11A817: | 50-600% |
| H11AA814A: | 50-150% | H11A817A: | 80-160% |
| H11A617A: | 40%-80% | H11A817B: | 130-260% |
| H11A617B: | 63%-125% | H11A817C: | 200-400% |
| H11A617C: | 100%-200% | H11A817D: | 300-600% |
| H11A617D: | 160%-320% | | |

- C-UL, UL and VDE approved
- High input-output isolation voltage of 5000Vrms
- Minimum $BV_{CEO}$ of 70V guaranteed

## Applications

H11AA814 Series
- AC line monitor
- Unknown polarity DC sensor
- Telephone line interface

H11A617 and H11A817 Series
- Power supply regulators
- Digital logic inputs
- Microprocessor inputs

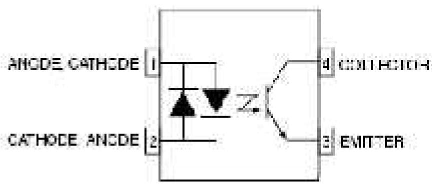
## Description

The H11AA814 consists of two gallium arsenide infrared emitting diodes, connected in inverse parallel, driving a silicon phototransistor output in a 4-pin dual in-line package. The H11A617/817 Series consists of a gallium arsenide infrared emitting diode driving a silicon phototransistor in a 4-pin dual in-line package.

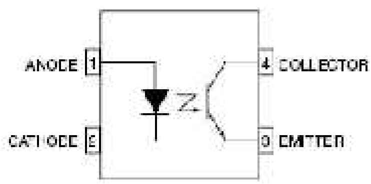
## Package

## Schematics

**H11AA814**




**H11A617 & H11A817**



## Absolute Maximum Ratings ($T_A$ = 25°C Unless otherwise specified.)

| Symbol | Parameter | Device* | Value | Units |
|---|---|---|---|---|
| **TOTAL DEVICE** | | | | |
| $T_{STG}$ | Storage Temperature | All | -55 to +150 | °C |
| $T_{OPR}$ | Operating Temperature | All | -55 to +100 | °C |
| $T_{SOL}$ | Lead Solder Temperature | All | 260 for 10 sec | °C |
| $P_D$ | Total Device Power Dissipation (-55°C to 50°C) | All | 200 | mW |
| **EMITTER** | | | | |
| $I_F$ | Continuous Forward Current | 814 Series<br>617, 817 Series | ±50<br>50 | mA |
| $V_R$ | Reverse Voltage | 617 Series<br>817 Series | 6<br>6 | V |
| $P_D$ | LED Power Dissipation (25°C ambient)<br>No derating up to 100°C | All | 70 | mW |
| **DETECTOR** | | | | |
| $V_{CEO}$ | Collector-Emitter Voltage | All | 70 | V |
| $V_{ECO}$ | Emitter-Collector Voltage | 814, 817 Series<br>617 Series | 6<br>7 | V |
| $I_C$ | Continuous Collector Current | All | 50 | mA |
| $P_D$ | Detector Power Dissipation (25°C ambient)<br>Derate above 90°C | All | 150<br>2.9 | mW<br>mW/°C |

## Electrical Characteristics ($T_A$ = 25°C Unless otherwise specified.)
## Individual Component Characteristics

| Symbol | Parameter | Test Conditions | Device | Min. | Typ.* | Max. | Unit |
|---|---|---|---|---|---|---|---|
| **EMITTER** | | | | | | | |
| $V_F$ | Input Forward Voltage | $I_F$ = 60mA | 617 Series | | 1.35 | 1.65 | V |
| | | $I_F$ = 20mA | 817 Series | | 1.2 | 1.5 | |
| | | $I_F$ = ±20mA | 814 Series | | 1.2 | 1.5 | |
| $I_R$ | Reverse Leakage Current | $V_R$ = 6.0V | 617 Series | | .001 | 10 | µA |
| | | $V_R$ = 5.0V | 817 Series | | | | |
| **DETECTOR** | | | | | | | |
| $BV_{CEO}$ | Collector-Emitter Breakdown Voltage | $I_C$ = 0.1 mA, $I_F$ = 0 | ALL | 70 | 100 | | V |
| $BV_{ECO}$ | Emitter-Collector Breakdown Voltage | $I_E$ = 10 µA, $I_F$ = 0 | 814, 817 Series | 6 | 10 | | V |
| | | | 617 Series | 7 | 10 | | |
| $I_{CEO}$ | Collector-Emitter Dark Current | $V_{CE}$ = 10V, $I_F$ = 0 | H11AA814/A, 617 Series, H11A617C/D | | 1 | 100 | nA |
| | | | H11A617A/B | | | 50 | |

*Typical values at $T_A$=25°C

## Transfer Characteristics ($T_A$ = 25°C Unless otherwise specified.)

| Symbol | DC Characteristic | Test Conditions | Device | Min | Typ* | Max | Unit |
|---|---|---|---|---|---|---|---|
| CTR | Current Transfer Ratio | $I_F$ = ±1mA, $V_{CE}$ = 5V(1) | H11AA814 | 20 | | 300 | % |
| | | $I_F$ = ±1mA, $V_{CE}$ = 5V(1) | H11AA814A | 50 | | 150 | % |
| | | ($I_F$ = 10mA, $V_{CE}$ = 5V(1) | H11A617A | 40 | | 80 | % |
| | | | H11A617B | 63 | | 125 | % |
| | | | H11A617C | 100 | | 200 | % |
| | | | H11A617D | 160 | | 320 | % |
| | | ($I_F$ = 5mA, $V_{CE}$ = 5V(1) | H11A817 | 50 | | 600 | % |
| | | | H11A817A | 80 | | 160 | % |
| | | | H11A817B | 130 | | 260 | % |
| | | | H11A817C | 200 | | 400 | % |
| | | | H11A817D | 300 | | 600 | % |
| | | $I_F$ = 1mA, $V_{CE}$ = 5V(1) | H11A617A | 13 | | | % |
| | | | H11A617B | 22 | | | % |
| | | | H11A617C | 34 | | | % |
| | | | H11A617D | 56 | | | % |
| $V_{CE(SAT)}$ | Collector-Emitter Saturation Voltage | $I_C$ = 1mA, $I_F$ = ±20mA | 814 series | | | 0.2 | V |
| | | $I_C$ = 2.5mA, $I_F$ = 10mA | 617 series | | | 0.4 | |
| | | $I_C$ = 1mA, $I_F$ = 20mA | 817 series | | | 0.2 | |
| **AC CHARACTERISTIC** | | | | | | | |
| $t_r$ | Rise Time | $I_C$ = 2mA, $V_{CE}$ = 2 V, $R_L$ = 100Ω(2) | ALL | | 4 | 18 | µs |
| $t_f$ | Fall Time | $I_C$ = 2mA, $V_{CE}$ = 2 V, $R_L$ = 100Ω(2) | ALL | | 3 | 18 | µs |

## Isolation Characteristics

| Symbol | Characteristic | Test Conditions | Min. | Typ.* | Max. | Units |
|---|---|---|---|---|---|---|
| $V_{ISO}$ | Input-Output Isolation Voltage (note 3) | (f = 60Hz, t = 1 min) ($I_{I-O}$ ≤ 2µA) | 5000 | | | Vac(rms) |
| $R_{ISO}$ | Isolation Resistance | ($V_{I-O}$ = 500 VDC) | $5x10^{10}$ | $10^{11}$ | | Ω |
| $C_{ISO}$ | Isolation Capacitance | ($V_{I-O}$ = 0, f = 1 MHz) | | 0.6 | 1.0 | pf |

*Typical values at $T_A$ = 25°C.

**Notes:**
1. Current Transfer Ratio (CTR) = $I_C/I_F$ x 100%.
2. For test circuit setup and waveforms, refer to Figure 13.
3. For this test, Pins 1 and 2 are common, and Pins 3 and 4 are common.

## Typical Performance Curves

Fig. 1 Current Transfer Ratio vs. Forward Current

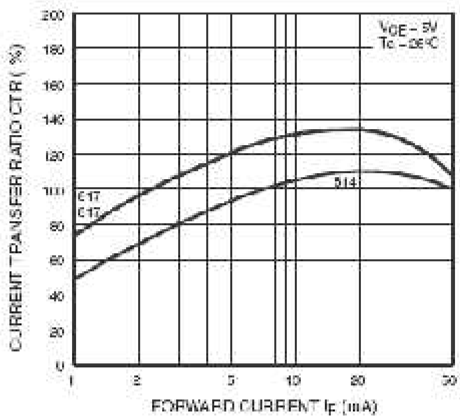


Fig. 2. Relative Current Transfer Ratio vs. Ambient Temperature

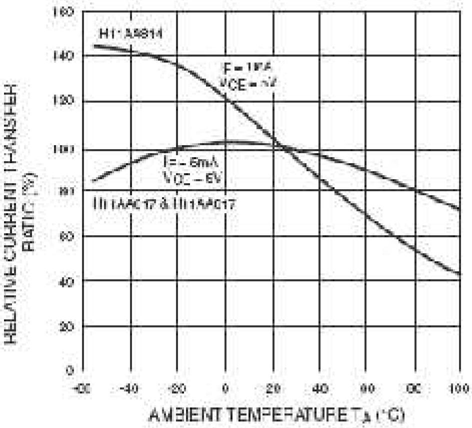


Fig. 3 Collector-Emitter Saturation Voltage vs. Ambient Temperature

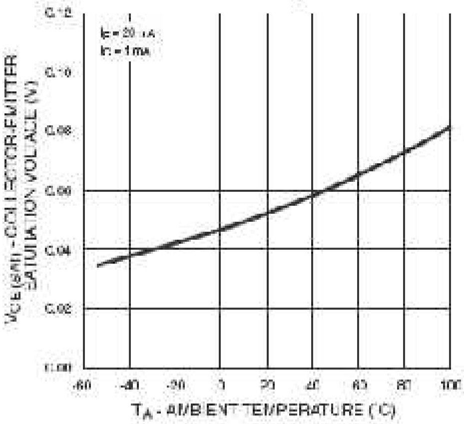


Fig. 4 Forward Current vs. Forward Voltage

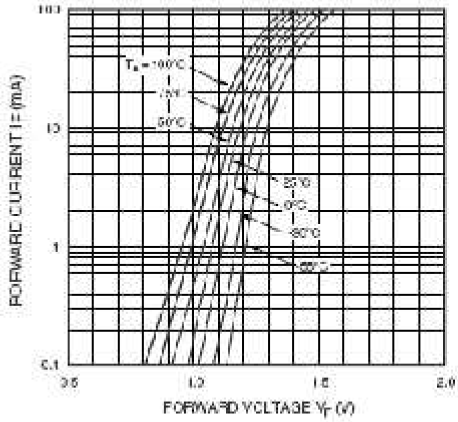


Fig. 5 Collector Current vs. Collector-Emitter Voltage (H11AA814)

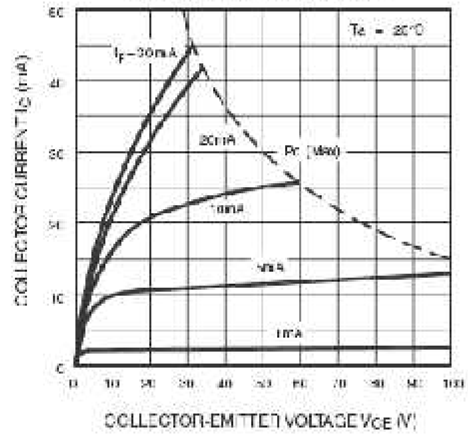
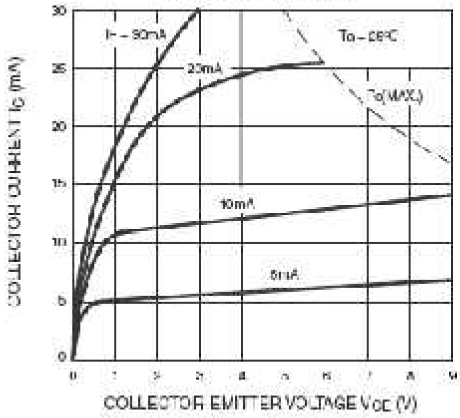


Fig. 6 Collector Current vs. Collector-Emitter Voltage (H11A617 and H11AA817)



## Typical Performance Curves (Continued)

Fig. 7. Collector Dark Current vs Ambient Temperature

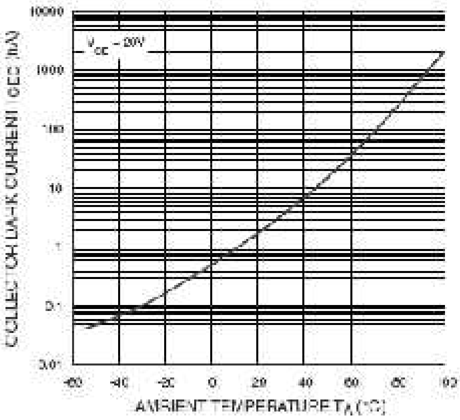


Fig. 8. Response Time vs. Load Resistance

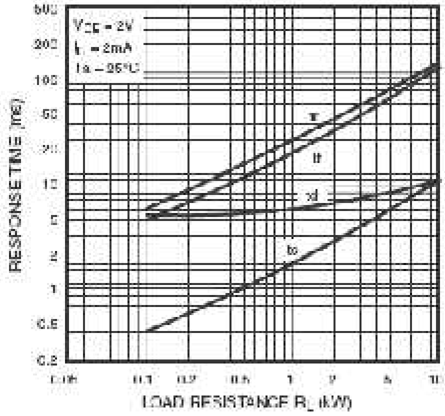


Fig. 9. Frequency Response (H11AA814)

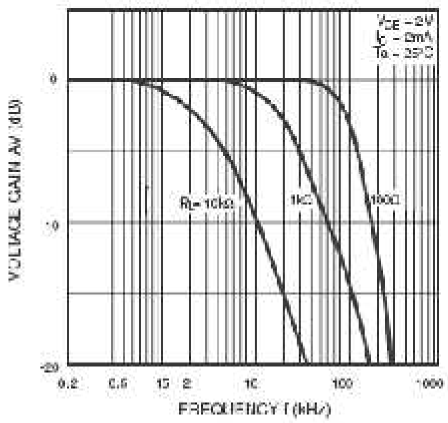


Fig. 10. Frequency Response (H11AA617 and H11A817)

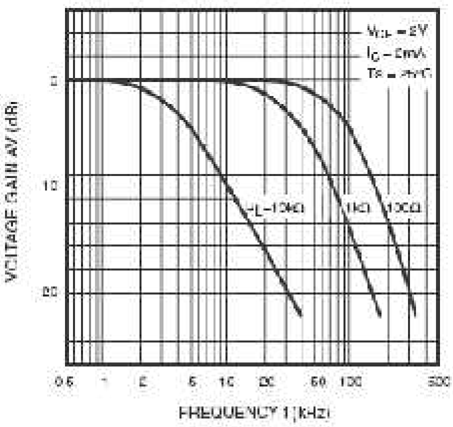


Fig. 11. LED Power Dissipation vs. Ambient Temperature

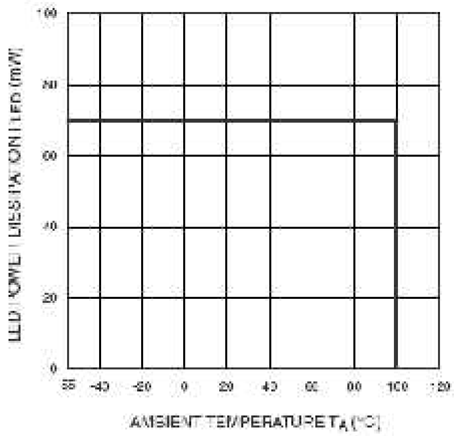
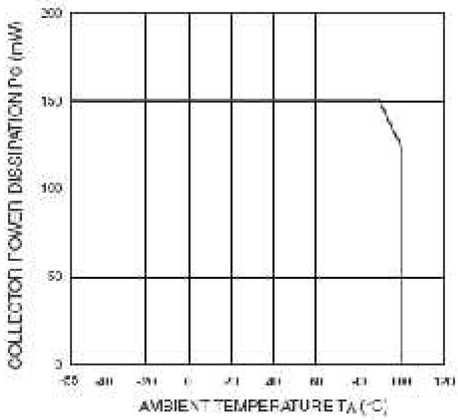
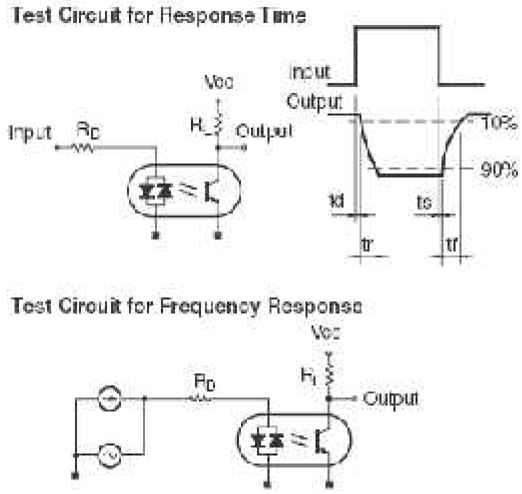


Fig. 12. Collector Power Dissipation vs. Ambient Temperature



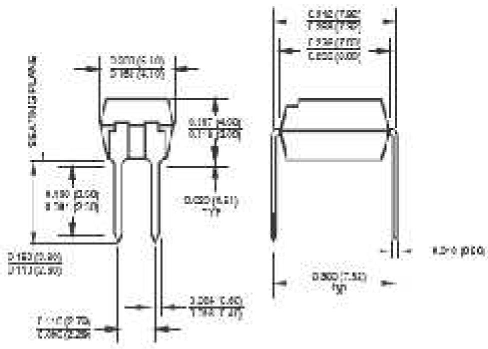
## Test Circuit

**Figure 13. Test Circuit**

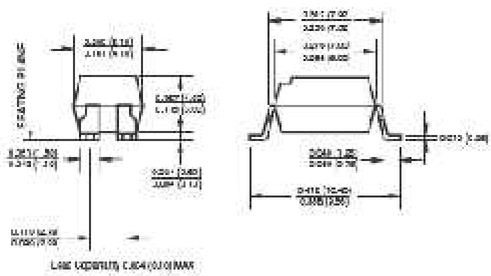


## Package Dimensions

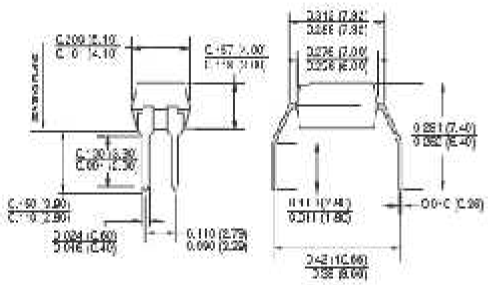
### Through Hole



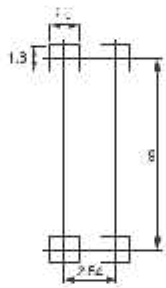
### Surface Mount



### 0.4" Lead Spacing



### Footprint Dimensions (Surface Mount)



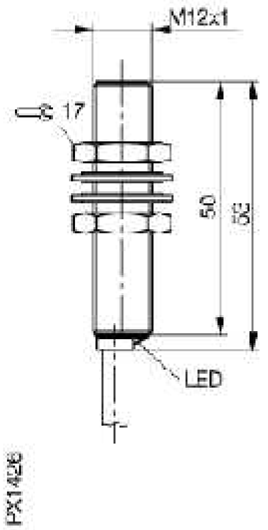
Note:
All dimensions are in inches (millimeters)

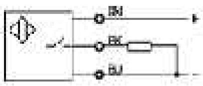
Inductive Sensors

# BES M12MI-PSC40B-BV03

**cyl. M12**
**Sn = 4 mm**
**DC 3-Wire**
**shielded**
**sn: 2fach**

BALLUFF
*sensors worldwide*

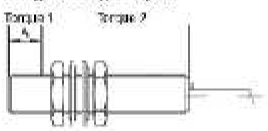



**Utilization categories DC 13**

**Further information:**
■ Einbauhinweise 825367

■ Tightening torque:




| | | |
|---|---|---|
| Torque 1 | Nm | 10 |
| Torque 2 | Nm | 15 |
| A | mm | 15 |

**If only torque1 is indicated, this applies to entire thread**

**If not differently indicated, all values by IEC 60947-5-2 (DIN EN60947-5-2)**
**Specifications subject to change**


**Balluff GmbH**
**Postfach 1160**
**73761 Neuhausen**
**Telefon (07158) 173-0**
**Telefax (07158) 5010**


## Common Data

| | | |
|---|---|---|
| **Mounting** | | shielded |
| **Rated operating distance Sn** | mm | 4.0 |
| **Assured operating distance Sa** | mm | 0...3.2 |
| **Repeatability** | % | <= 5 |
| **Hysteresis** | % | <= 15 |
| **Function indication** | | yes |
| **Ambient temperature range** | °C | -25...+70 |
| **Polution Degree** | | 3 |
| **IEC-Code** | | I1A12AP1 |
| **Time delay before availability** | ms | <= 30 |

## Mechanical Data

| | | |
|---|---|---|
| **Housing size** | mm | cyl. M12 |
| **Measurements BxHxT or DxT** | mm | M12x1 x 55 |
| **Housing material** | | nickel plated brass |
| **Material of sensing face** | | LCP |
| **Degree of protection** | | 68 acc. BWN Pr 20 |
| **Connection** | | Cable |
| **Cable type** | | LIYY-O, 3x0,34mm² |

## Electrical Data

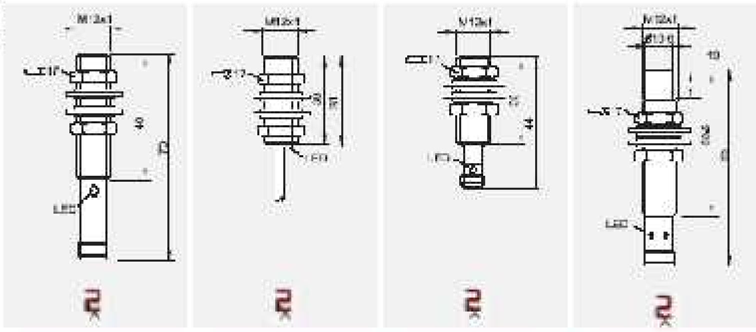
| | | |
|---|---|---|
| **Current type** | | DC |
| **Wiring** | | 3-Wire |
| **switching function** | | normally-open |
| **Output signal** | | PNP |
| **Rated operational voltage** | V | 24 DC |
| **Rated operational current** | mA | 200 |
| **Supply voltage** | V | 12...30 DC |
| **Ripple** | % | <= 15 |
| **Rated supply frequency** | Hz | 300 |
| **No-load supply current** | mA | <= 15 |
| **Off-state current** | µA | <= 20 |
| **Voltage drop** | V | <= 2.5 |
| **Short circuit protection** | | yes |
| **Protected against polarity reversal** | | yes |


29.08.2006 / Online-Information

**Inductive Sensors** DC 3-/4-Wire M12 $s_n$ 4 mm, 8 mm

**2X HyperPROX™** Long Range Inductive Sensors

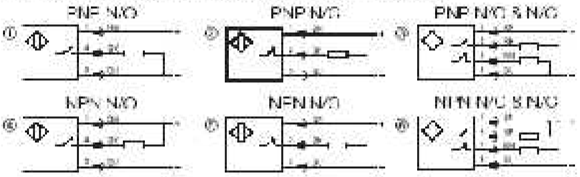
| | | | | |
|---|---|---|---|---|
| Housing size | M12x1 | M12x1 | M12x1 | M12x1 |
| Mounting | flush | flush | flush | non flush |
| Rated operating distance $s_n$ | 4 mm | 4 mm | 4 mm | 8 mm |
| Assured operating distance $s_a$ | 0...3.2 mm | 0...3.2 mm | 0...3.2 mm | 0...6.4 mm |




| | | | | |
|---|---|---|---|---|
| PNP Normally-open ① | BES-516-325-G-S4-C | BES-516-325-G-E4-Y | BES-516-325-G-E5-Y-S49 | BES-M12EG-PSC80F-S04G |
| Normally-closed ② | | BES-516-370-G-E4-Y | BES-516-370-G-E5-Y-S49 | |
| Complementary ③ | | | | |
| NPN Normally-open ④ | | BES-516-320-G-E4-Y | BES 516 329 G E5 Y S49 | BES 516 367 G BA 6 S4 C |
| Normally-closed ⑤ | | BES-516-375-G-E4-Y | BES 516 375 G E5 Y S49 | |
| Rated operational voltage $U_e$ | 24 Vdc | 24 Vdc | 24 Vdc | 24 Vdc |
| Supply voltage $U_B$ | 10...30 Vdc | 10...30 Vdc | 10...30 Vdc | 10...30 Vdc |
| Voltage drop $U_d$ at $I_e$ | ≤ 2.5 V | ≤ 3.5 V | ≤ 3.5 V | ≤ 2.0 V |
| Rated insulation voltage $U_i$ | 250 Vac | 75 Vdc | 75 Vdc | 250 Vac |
| Load current capacity | 200 mA | 130 mA | 130 mA | 200 mA |
| Current consumption (closed/open) | ≤ 12 mA/≤ 4 mA | ≤ 25 mA/≤ 12 mA | ≤ 25 mA/≤ 12 mA | ≤ 12 mA/10 mA |
| Off state current $I_r$ | ≤ 80 µA | ≤ 80 µA | ≤ 80 µA | ≤ 80 µA |
| Protected against polarity reversal | yes | yes | yes | yes |
| Short circuit protected | yes | yes | yes | yes |
| Load capacitance | ≤ 1.0 µF | ≤ 1.0 µF | ≤ 1.0 µF | ≤ 0.15 µF |
| Repeat accuracy R | ≤ 5 % | ≤ 5 % | ≤ 5 % | ≤ 5 % |
| Ambient temperature range $T_a$ | -25...+70 °C | -25...+70 °C | -25...+70 °C | -25...+70 °C |
| Frequency of operating cycles f | 1000 Hz | 800 Hz | 800 Hz | 1500 Hz |
| Utilization categories | DC 13 | DC 13 | DC 13 | DC 13 |
| Function indication | yes | yes | yes | yes |
| Degree of protection per IEC 529 | IP 68 | IP 68 | IP 67 | IP 68 |
| Insulation class | ⊡ | | | ⊡ |
| Housing material | nickel plated brass | nickel plated brass | nickel plated brass | stainless steel |
| Material of sensing face | LCP | PA 12 | PA 12 | PETP |
| Connection | connector | cable | connector | connector |
| No. of wires x gauge | | 3 x 22 AWG | | |
| Approvals | cULus | cULus | cULus | |
| Recommended connector | C04-ATL-00-VY-050M | | C49-ANE-00-VY-050M | C04-AEL-00-VY-050M |

*See page 21 for proper mounting of the 2x sensors

Please add the cable length to the ordering code for sensors with molded cable!
03, 05 = PVC 3 m or 5 m length
PU 03, PU 05 = PuRex 3 m or 5 m length



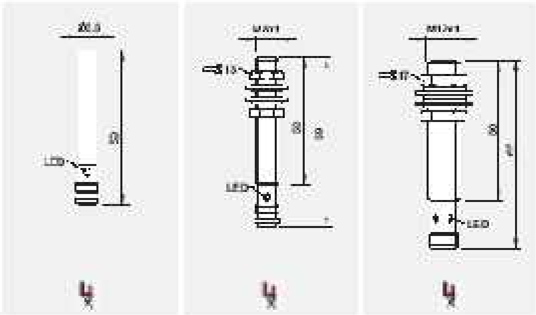
# Inductive Sensors

DC 3 Wire
Ø 6.5mm, M8, M12
$s_n$ 4mm, 8mm

4X HyperPROX™
Long Range Inductive Sensors

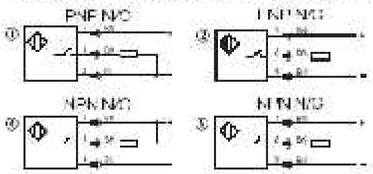
| | | | |
|---|---|---|---|
| Housing size | Ø 6.5mm | M8x1 | M12x1 |
| Mounting | quasi-flush | quasi-flush | quasi-flush |
| Rated operating distance $s_n$ | 4mm | 4 mm | 8 mm |
| Assured operating distance $s_a$ | 0...2.9mm | 0...2.9 mm | 0...5.8 mm |

CE



| | | | |
|---|---|---|---|
| PNP Normally-open ① | BES-G06M-PSC40B-S49G | BES-M08MI-PSC40B-S49G | BES-M12MI-PSH80B-S04G |
| Normally-closed ② | | | |
| NPN Normally-open ③ | | | BES-M12MI-NSH80B-S04G |
| Normally-closed ④ | | | |
| Rated operational voltage $U_e$ | 24 Vdc | 24 Vdc | 24 Vdc |
| Supply voltage $U_B$ | 10...30 Vdc | 10...30 Vdc | 10...55 Vdc |
| Voltage drop $U_d$ at $I_e$ | ≤ 2.8 V | ≤ 2.8 V | ≤ 2.5 V |
| Rated insulation voltage $U_i$ | 75 Vdc | 75 Vdc | 250 Vac |
| Load current capacity | 200 mA | 200 mA | 200 mA |
| Current consumption (closed/open) | ≤ 10 mA/≤ 8 mA | ≤ 10 mA/≤ 8 mA | ≤ 10 mA/≤ 8 mA |
| Off-state current $I_r$ | ≤ 10 µA | ≤ 10 µA | ≤ 10 µA |
| Protected against polarity reversal | yes | yes | yes |
| Short circuit protected | yes | yes | yes |
| Load capacitance | ≤ 1.0 µF | ≤ 1.0 µF | ≤ 1.0 µF |
| Repeat accuracy R | ≤ 5 % | ≤ 5 % | ≤ 10 % |
| Ambient temperature range $T_a$ | 0...+60 °C | 0...+60 °C | 0...+60 °C |
| Frequency of operating cycles f | 800 Hz | 800 Hz | 300 Hz |
| Utilization categories | DC 13 | DC 13 | DC 13 |
| Function indication | yes | yes | yes |
| Degree of protection per IEC 529 | IP 67 | IP 67 | IP 67 |
| Insulation Class | | | III |
| Housing material | CuZn nickel plated | CuZn nickel plated | CuZn nickel plated |
| Material of sensing face | PBTP | PBTP | LCP |
| Connection | connector | connector | connector |
| No. of wires x gauge | | | |
| Approvals | cULus | cULus | |
| Recommended connector | C49-ANE-00-VY-050M | C49-ANE-00-VY-050M | C04-AEL-00-VY-050M |

*See page 21 for proper mounting of the 4x sensors




# Hyper 2X 3X 4X PROX®
Long Range Inductive Sensors

## Reduce replacement costs!

The most common cause of sensor failure is contact with the intended target. By eliminating contact with the target, you will reduce costs associated with replacing damaged sensors including the cost of the sensor, maintenance time, and lost production.

Target impact to standard sensors pulled from real-world applications.

## Attack your toughest applications.

Balluff HyperPROX™ long range inductives are perfect for your most difficult applications, especially in harsh environments where other sensors may not be reliable.

## Choose the alternative to steel-faced sensors.

Some applications are too rugged for even the toughest of steel faced sensors. These environments require a unique solution - avoiding contact altogether with Balluff's long range HyperPROX™ sensors.

Typical damage to steel-faced sensors caused by contact with the target.

# Avoid contact with long range inductives!

## Long range inductives solve the most difficult challenges in a variety of applications!

- Small part detection
- Machines with excessive vibration
- Broken bit detection
- Machines with mechanical misalignment
- Detecting metal embedded in non-metal parts

Parts on a conveyor

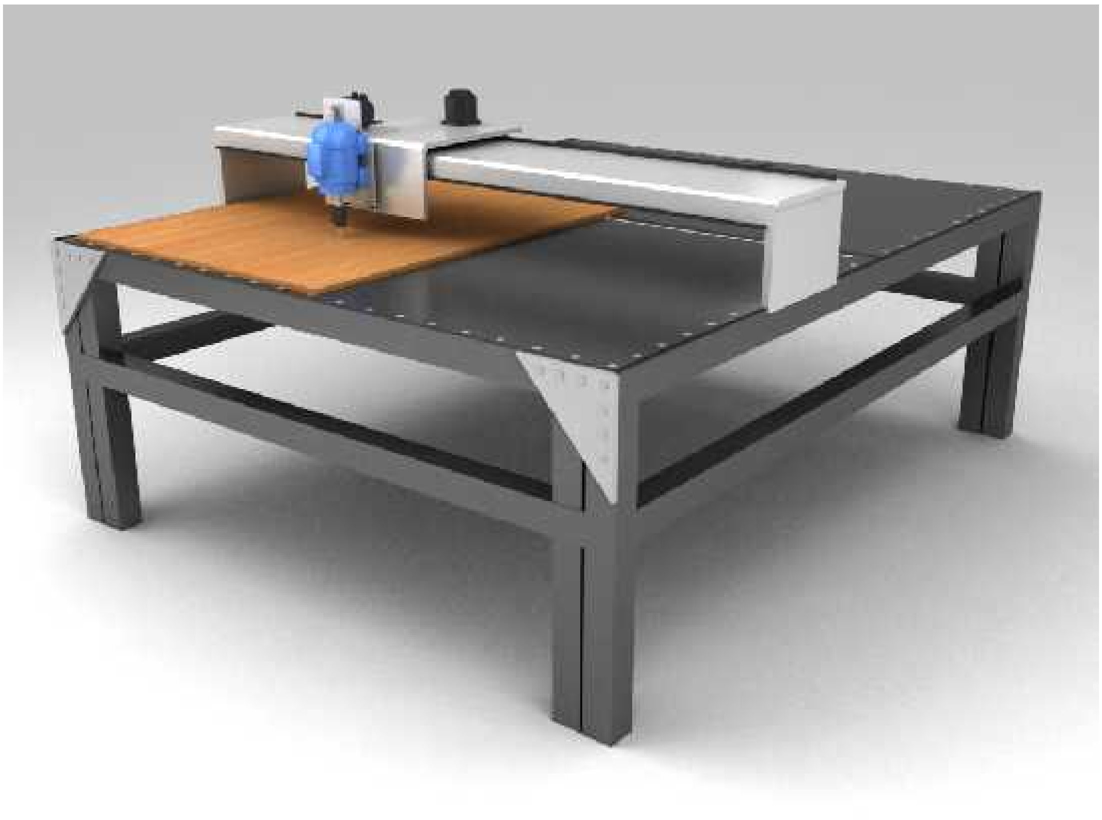
Metal Flexing

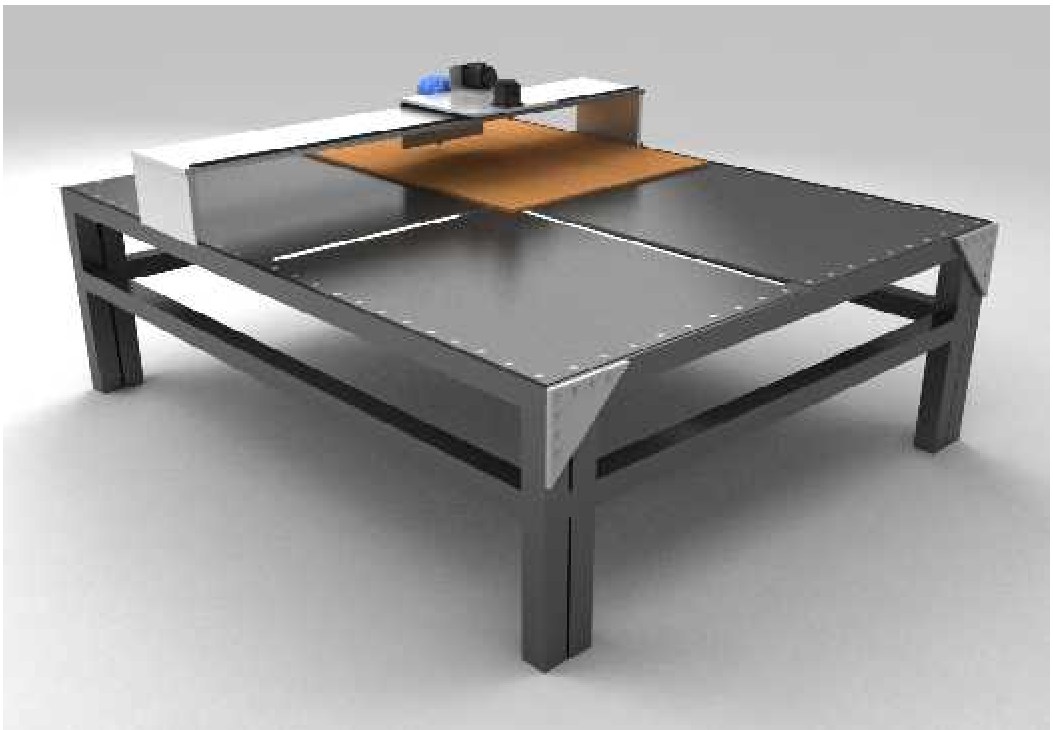
Travel Limit

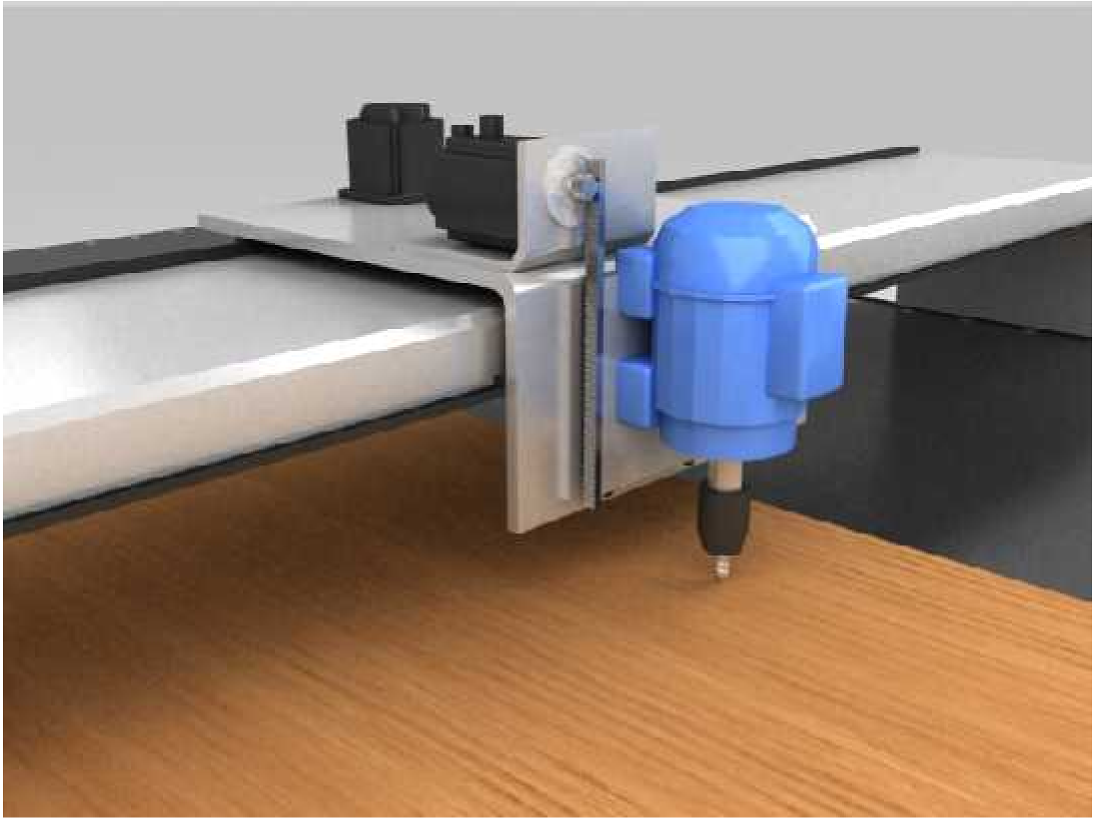
Mis-alignment

# Appendix C

## Machine Pictures





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