بسم الله الرحمن الرحيم

PPU College Of
Engineering and Technology
The Home of Competent Engineers and Researchers

Mechanical Engineering Department

Mechatronics Engineering Program

Bachelor Thesis

Graduation Project

Laser Bridge Coordinate Measuring Machine

Project Team

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Hebron – Palestine

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Palestine Polytechnic University

College of Engineering and Technology

Mechanical Engineering Department

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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 mechanical 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

Mechanical Engineering Department

Our supervisor Eng. Majdi Zalloum for his helps and support
To Dr. Yousef Swaiti

To any one whom helped us.

Abstract

A coordinate measuring machine (CMM) is a device for measuring the physical geometrical characteristics of an object.It poses significant importance in technology, especially when precise geometric modeling is required.

Measuring complicated, high precision objects is crucial for today’s manufacturing industries, and much technology has been developed for these operations. This technology enables the manufacturer a fast easy way to measure and model wanted areas for faster production processes and negligible lost time. The proper use of these machines can result in high resolution modeling and cost reducing methodology.

Measurements are defined by a probe attached to the third moving axis of a bridge machine. Probes may be mechanical, optical, laser, or white light, amongst others. The sensor that we want to implement in our project is a laser triangulation sensor. This sensor provides accurate measurements up to one micrometer resolution and is easy to use due to its non-contact nature.

The bridgemachineis actuated bythree motors(in general), and three sensors for coordinate feedback. The three motors are used to control the movement of the laser triangulation sensorin the x, y, and z directions. Feedback is provided by the optical encoders in the x and y axes provided with the reading of the laser triangulation sensor (z-axis) for a point cloud demonstration. In addition to that, a potentiometer in the z axis provides feedback to its respective motor. The movement of the motors is restricted to a specific range determined by the sensors' feedback.

The basic schematic of the CMM is shown in Figure1:

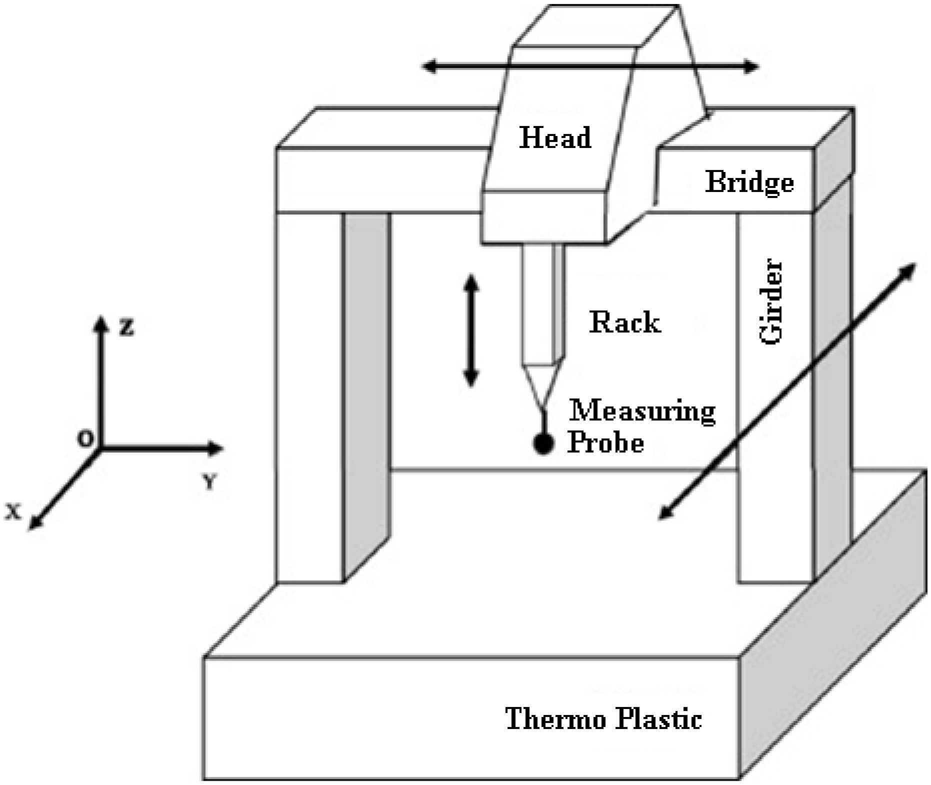

Figure I.1: coordinate measuring machine

الملخص

آلة قياس الأبعاد (CMM) هي عبارة عن آلة تقوم بقياس الخصائص الفيزيائية الهندسية للعينة المراد قياس أبعادها.

يتم اخذ القياسات للعينة عن طريق حساس ليزري مثبت على عمود محوره (ع) . وفي هذا البحث العلمي سوف يتوفر لنا الفهم العميق لآلية عمل هذا الحساس ولمعرفة آلية التحكم بحركة النظام الميكانيكي. حيث أن طريقة التفاعل والارتباط بين هذين النظامين ذو أهمية عالية وكبيرة.

سبب استخدام هذه الآلة بدلا من عملية القياس اليدوية للعينات أن هذه الآلة تعمل بآلية سريعة ودقيقة لفحص العينات المصنعة , والتي تعتبر منخفضة التكلفة نسبيا واقل استهلاكا للوقت.

لتحقيق نظام عمل الآلة بالمعايير المطلوبة , فانه يلزم عمل إحدى هذين النظامين للتحكم :
إما نظام PD وإما PID . حيث عملية الاختيار بين هذين النظامين تعتمد على سهولة التحكم , استجابة النظام للوقت ,مدى التحكم للسرعة ولتحديد النقطة التي يريد الذهاب إليها.

مرونة التعامل مع أجهزة الحاسوب , وجعل عملية التحكم أكثر أمانا و سهولة , أيضا لان عملية القياس تحتاج إلى دقة عالية وسرعة الاستجابة والتحكم بالأبعاد الثلاثة (س,ص,ع) , جميع هذه العوامل ساعدت على الوصول إلى هذه الآلة , آلة قياس الأبعاد.

هذه الآلة تتكون بشكل عام من ثلاثة محركات و حساسات. المحركات الثلاثة تستخدم للتحكم بحركة ذراع الليزر الذي يعمل على قياس الأبعاد في الاتجاهات الثلاثة (س,ص,ع). وحركة المحركات تقتصر على مدى محدد تعمل فيه يتحكم بذلك الحساسات.

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Chapter One 1

Introduction

1.1 Entrance to Graduation Project:

In the mechatronics environment, implementation of certain ideas is crucial for deep understanding. This implementation can be done by research and by physical simulation and testing. Regarding this, the main idea that we want to study and physically implement is called the “laser bridge coordinate measuring machine”. This machine falls in the coordinate measuring machines categories. This project will implement the idea of measurement and sensory as well as motion and feedback control. It will provide us with a deep understanding of the working principles of the laser modeling system and the motion control system. Also, the interfacing between these two systems will be of great significance. Concluding this, if the idea is well researched and implemented, it will be a strong example of the mechatronics concurrent design methodology.

1.2 Coordinate Measuring Machines Overview:

Coordinate Measuring machines (CMM) pose significant importance in technology, especially when precise geometric modeling is required. Measuring complicated, high precision objects is crucial for today’s manufacturing industries, and much technology has been developed for these operations. This technology enables the manufacturer a fast easy way to measure and model wanted areas for faster production processes and negligible lost time. The proper use of these machines can result in high resolution modeling and cost reducing methodology.

1.3 Project Objectives

The main objectives of this project are:

1. Use the CMM in colleges and universities as an educational tool because it combines many technological systems.
2. Highlight the integration between the software programming and mechanical designing.
3. Establish a connection between a personal computer and the LBCMM for automatic machine mode.
4. Extract a text file consisting of coordinate points that describe the object.
5. Enabling a manual mode for easy use and user comfort.
6. Setting a resolution that the user commands based on the existing time that he can offer.

1.4 Recognition of the Need

The CMM considers many important technologies, since it comprises several technical specialties: electrical, computer, and mechanical techniques.

Since the use of the computer is flexible and it makes the control of the machine more safe, easier, and faster; and due to that the measuring operation need high accuracy, difficult time response, high range for speed and position control, and control of three dimensions, it is represented as the main controller, by this we reached a high technical machine which is the coordinate measuring machine (CMM).

1.5 Project Description:

The working principle of CMM is defined by a system that moves in three dimensions (X,Y, and Z). Zigzag movement is applied in the X axis and Y axis, while vertical movement is applied for Z axis. The purpose of the CMM is to apply these movements in order to measure the dimensions of the sample by laser sensory, and then represent the wave or real image with dimensions of the sample in a computer software program.

Then, the image can be used to remanufacturing a copy of the sample with accurate dimensions.

1.6 Classification of CMMs:

In the CAD/CAM environment, CMMs are used in order to measure geometries of different parts. CMMs can quickly and easily measure geometries and precisely model them. There are many types of CMMs available, serving design and manufacturing needs. Some of these types are described below:

Articulated Arm

The articulated arm is a non-orthogonal CMM. It can be either portable or tripod mounted. Also the probes can be placed in many different directions. These arms have six or seven rotary axes with rotary encoders, instead of linear axes. By calculating mathematically the values read in these encoders, the articulated arm will provide the x, y and z coordinates that are required to work in a Euclidian space, where it will behave just like a conventional CMM.

Bridge

The Bridge CMM is composed of three axes (X, Y and Z). These axes are orthogonal to each other in a typical three dimensional coordinate system. Each axis has a scale system that indicates the location of that axis. The x-axis carries the bridge. This is the CMM type that we have chosen to build. This is because of its simplicity and its high flexibility. Also, this machine can be adjusted for additional applications such as “milling after scanning”.

Cantilever
A Cantilever CMM is a type of CMM with a single, moveable vertical support that suspends a horizontal arm that holds the probe. Cantilever CMMs provide easy access to the staging table.

Gantry
Gantry styles CMMs have a frame structure raised on side supports so as to span over the object to be measured or scanned. Gantry machines are similar in construction to bridge style designs but much larger. Gantry CMMs can measure parts the size of a car.

Fig. 1.1 Articulated Arms (1)

Fig. 1.2 Bridge CMM (2)

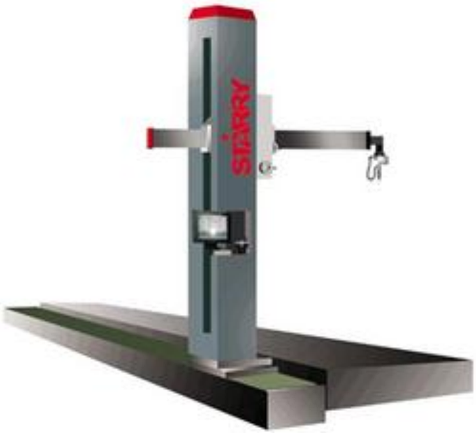


Fig. 1.3 Cantilever CMM (3)

Horizontal Arm
In horizontal arm CMMs, the arm that supports the probe is horizontally cantilevered from a movable vertical support. As a result, this style is sometimes referred to as cantilever.

Fig. 1.4 Gantry CMM (4)

Fig. 1.5 Horizontal Arm CMM (5)

Coordinate measuring machines can have one of several mounting options. They include bench top, free standing, handheld and portable. Probe systems for CMMs can be touch probe or discrete point, laser triangulation, camera or still and video camera.

1.7 CMM Structure:

There are many structures found for the CMMs in wide variety. Many of which are for special purpose use in manufacturing and research and others for regular wide spread measuring purposes. The bridge CMM is a multipurpose general and special use structure built in many forms for different measuring applications including nanotechnology measuring. The main structure of the bridge CMM is shown below.

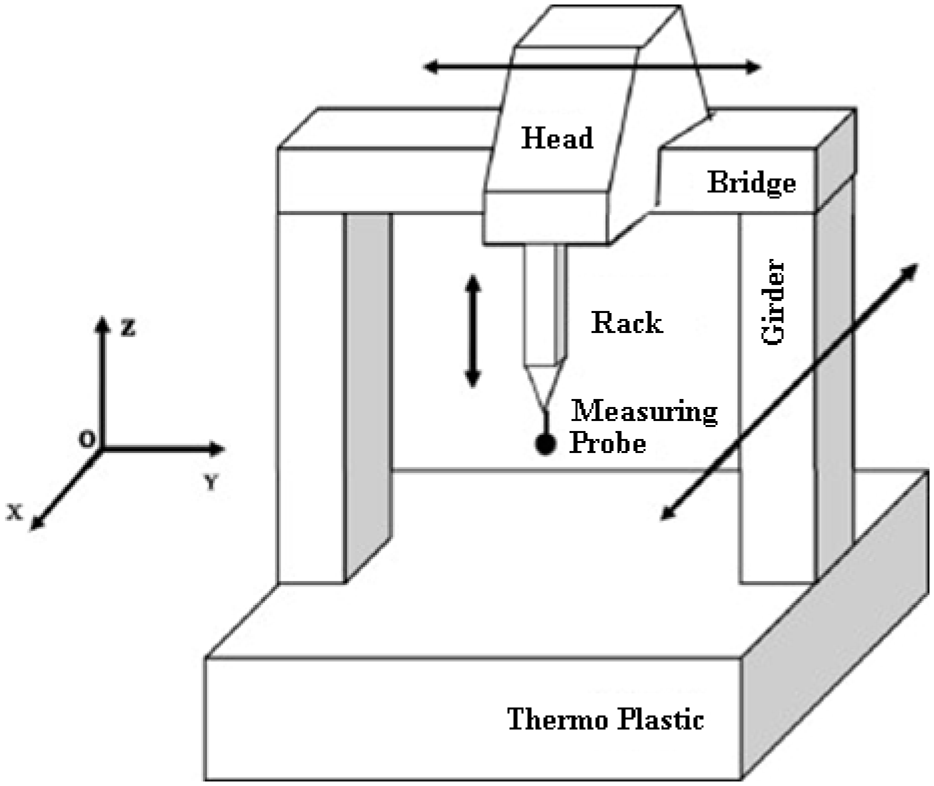


Fig. 1.6 CMM Mechanical Structure (6)

As shown in Fig. 1.6, the bridge CMM comprises the following components:

1) Bridge
2) Table (thermoplastic for light weight (up to 100 kg) purposes)
3) Arm
4) Probe
5) Drives(Motors, engines, hydraulic drives)

Fig. 1.6 illustrates an articulating probe head mounted on a coordinate measuring machine. The coordinate measuring machine comprises a table on which a work piece may be placed and an arm movable in X, Y and Z relative to the table. An articulating probe head is mounted on the arm of the CMM.

The machine arm may therefore be moved in X, Y and Z directions under the action of X, Y and Z drives of the coordinate measuring machine. X, Y, and Z scales show the instantaneous coordinates of the position of the arm. Signals from the probe indicating the deflection of the probe stylus are combined with the readings from the X, Y and Z scales of the CMM to calculate the position of the stylus tip (in our case laser reflection) and thus the surface of the work piece.

1.8 Microcontroller

A microcontroller (MCU) is a small computer on a single integrated circuit containing a processor core, memory, and programmable input/output peripherals.[7]

Microcontrollers are used in automatically controlled products and devices, such as the CMM machine. For the CMM we have chosen the PIC18F87k22 due to its features as shown in appendix I.

1.9 Laser (Bridge) Coordinate Measuring System:

This system is also called”3D Laser Scanner”. It is the project intended to be built, experimented with, and controlled. This system is a great example of industrial control and is a huge controversy between engineers. Many articles have been written on it exposing ideas of evolution and higher level control benefiting the manufacturing procedures. A brief description of the system and “how it works” is explained below.

Fig. 1.7 3D Laser Scanner (8)

This device analyzes a real-world object in order to collect data on its shape. The main structure of this machine includes three axes of motion. The probing system used is laser triangulation with high level technology. The machine is run by electrical drives with feed forward and feedback systems. High movement accuracy is achieved by this electrical drive provoking high precision coordinate estimation and modeling.

As visualized from the figure above, the head moves in a horizontal-axis on the bridge by a controlled rotating ball screw drive. This head with the help of the arm will carry the laser scanning probe. In addition, the bridge moves along the vertical axis by another rotating ball screw drive with additional support. At the ends of the screws, there is usually limit switches installed so that the head and the bridge can only travel to the limits without damaging the structure. This system is interfaced by a control panel and can be modified using the computer. Finally, results are presented on a screen with coordinate estimation and overall measurement modeling.

1.10 Scanning Method:

The scanning method of the LBCMM can be summarized in the following steps:

1- The machine will perform homing or referencing as soon as the machine is turned on where the probe will go to the highest point possible and the girder and head will move to a reference point indicated by limit switches for precise calibration of the machine.

2- Then the user will be asked to choose automatic mode or manual mode by flipping a single pole double throw switch and pressing enter. These modes will be discussed below.
*note: Manual mode instructions start from point 4 to point 6 while automatic mode instructions start from point 7 to point 9.

3- If Manual mode is chosen, then the user may be able to move the machine girder, head, and probe freely as they like until they reach the initial point they want to start the scan from.

4- When the user reaches the initial point, then they must press a push button indicated by “start scan”.

5- After the “start scan” push button is pressed the probe becomes fixed and the girder and the head may move freely by the user while scan data is sent to the computer directly.

6- After scanning the particular part, the user presses the “scan finished” push button to stop sending data to the computer.

7- If manual mode is chosen then the user is obligated to use the computer software in order to perform scan.

8- On the software, the user must enter the initial point coordinate (x, y), final point coordinate (x, y), the highest landscape point in the object (z), the speed of the motors, resolution of the scan, and the sampling time.

9- If all of the inputs are bounded inside the scope of the software, the user might as well press the scan icon where the machine will start scanning in a zigzag like motion.
10- When the scan is finished by means of manual or automatic mode, the coordinate points are stored as a large three column matrix inside a text file.
11- The text file has to then be converted to an ascii file for further treatment.
12- The ascii file is then sent as a point cloud on the catia software where a 3-D precise image is resulted.
13- To perform another scan, the reset push button must be pressed.

The machine built is intended to have two modes of operation, manual and automatic. Manual mode enables the user to move the device freely as they want and to scan an irregular shape without wasting any time scanning an unimportant area. This feature is very important for practical operations where the automatic mode fails to fulfill the users need. As for the automatic mode, the user will just input data into the machine for a full scan operation without the need to waste his time watching over it manually. This feature is very important because of its ease of use and its high quality options.

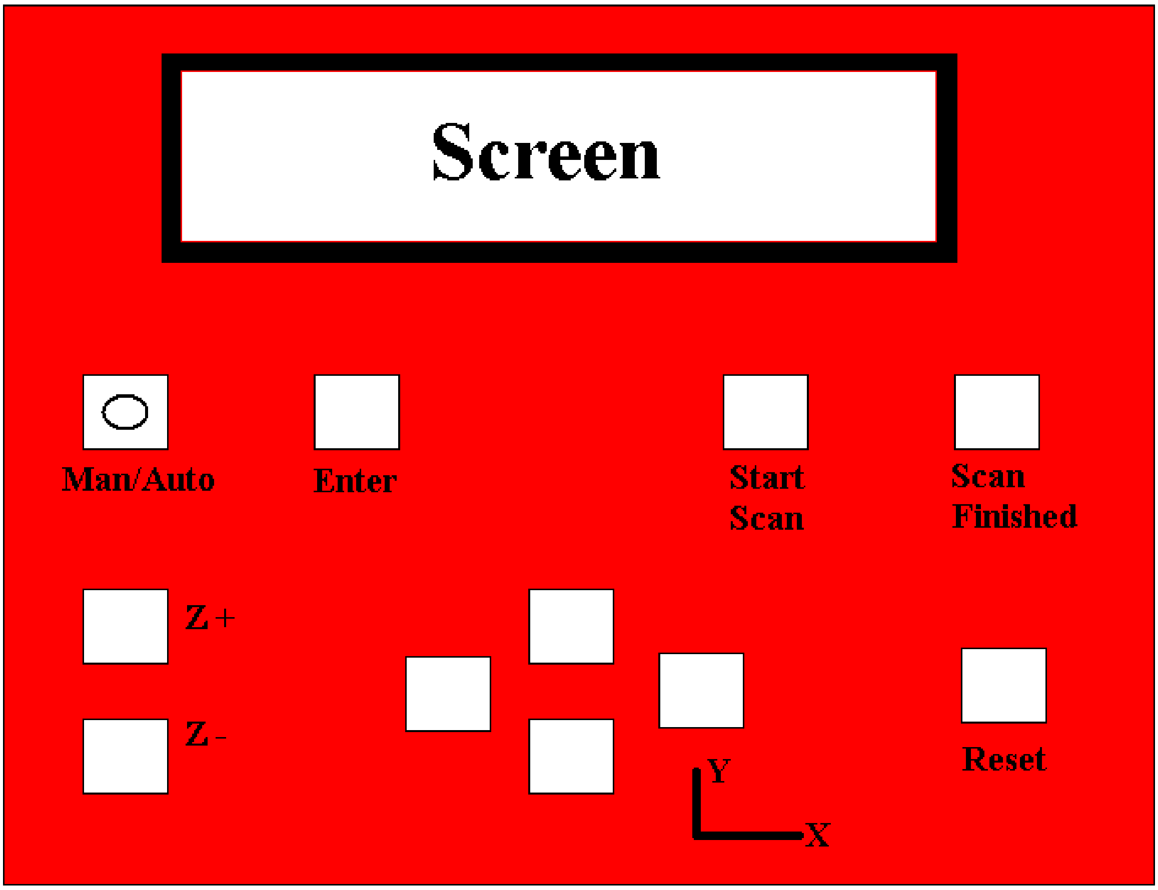


Fig. 1.8 User Control Panel

The guided user interface is demonstrated in appendix III while the user control panel is shown below. Also, the zigzag motion performed in automatic mode is shown below.

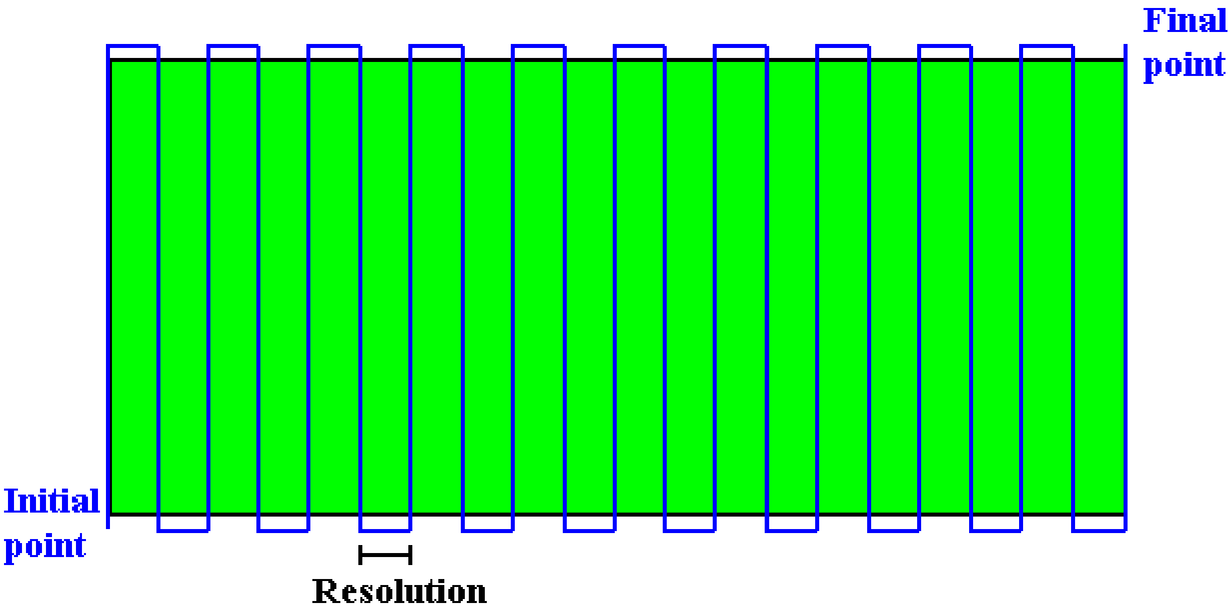


Fig. 1.9 Automatic Zigzag movement

1.11 Project Overview:

There are many goals to be achieved in this project. Even though the Laser CMM has been made and experimented with many times, there is a lack of consensus revolving around calibration, precision, and referencing. The need to control a traveling probe in order to measure and model an object with the high precision and eliminating losses in time is of great importance. Furthermore, problematic errors due to speed and position probe calibration should be eliminated in order for the system to work properly. This can all be pursued by following a concurrent design methodology where mechanics, electronics, and control are all synergistically integrated. Concluding this, our responsibility is to attain this intelligent problem-free Laser CMM and implement it for realistic modeling.

1.12 Project Scheduling and Financial Distribution:

The Project's working schedule in the first and second semesters are shown in the following tables respectively.

Table (1.1): First Semester Timing Table

Week Activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Choosing the project	🟩	🟩	🟩	🟩	🟩	🟩										
Gathering information about the project					🟩	🟩	🟩	🟩								
Sensors and actuators information									🟩	🟩	🟩	🟩				
Mechanical analysis									🟩	🟩	🟩	🟩				
Control Analysis													🟩	🟩	🟩	
Documentation	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Table (1.2): Second Semester Timing Table

Week Activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Updating Design	🟩	🟩														
Gathering Mechanical components	🟩	🟩	🟩	🟩												
Gathering Actuators	🟩	🟩	🟩	🟩	🟩	🟩	🟩									
Building Mechanical Structure	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩						
Gathering Sensors	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
Designing And Building Electrical Circuits						🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
Shape Finishing														🟩	🟩	🟩
Programming And Control	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Documentation	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

The cost of the project at precisely studied, most of the project parts are available in local market but some are not, such as the Laser sensor which is relatively expensive. The Parts and its price on their land are listed in Table (1.3).

Table (1.3): Parts Price Table

Components	**Cost ($)**
Laser sensor + Microcontrollers	$1000
Motors(3) + Encoders(2)	$300(used)
Mechanical Structure	$600(free machining)
Transportation	$300
Electrical Drivers	$450
Electronics	$200
Total cost	$2850

*note: This project was supported by the Deanship of Scientific Research and the center of mechanical services an amount of 500 JD and 300JD respectively.

1.13 Summary:

Coordinate Measuring Machine is a scientific application that combines hardware with software, programming with designing and entertainment with science. The integration between the physical parts such as the mechanical structure and the motors is important, but the core of this importance is beyond the integration between the physical parts and the software on the PC.

This chapter presented the general ideas of coordinate measuring machine, the system objectives, system description, and recognition of the need. Chapter two talks about system analysis, physical component, and generating the dynamic behavior equations.

Chapter three presents the system requirements, such as electric actuators, mechanical actuators, sensors and the power supplies for the motor drivers and overall system. Chapter four talks about system integration and control where we applied the dynamic equations that were generated in chapter two. Chapter five shows the testing results of the machine and views the conclusion of these results.

Chapter Two 2

Physical System Analysis

2.1 Overview:

In this chapter, pure mechanical analysis will be constructed. This will be conducted by first explaining the physical components of the laser CMM. These components will be shown into four main categories. Each of these categories is chosen either according to the construction or movement of a complete sub-system. Later in this chapter, we will go through the dynamic behavior of this system. This will be explained by imposing first physical principles and working them up into differential equations. By this analysis, we can linearize and state space model these equations in order for further results. Also, this work will make simulation achievable for further analysis.

2.2 Physical Components of the Laser CMM:

The laser CMM is divided up into four basic physical components depending on the function and the movement of the subsystems. These components interplay in order to emphasize a real-time controlled process. These components are the machine base, x-axis assembly, y-axis assembly, and the z-axis assembly.

2.2.1 The Machine Base:

The base is the rectangular fixed component (table) which will be made out of thermoplastic. It is where the part needed to be measured will be placed on and clamped to in order to obtain a fixed posture. Other references may call this component the “bed”. This is because it is where the parts needed to be measured are laid.

2.2.2 X-axis Assembly:

The physical assembly of the x-axis comprises the following parts:

1- Ball Screw Drive: a ball screw drive is a mechanism where a nut with internal frictionless balls moves along a screw (square thread or ACME). Moving parts can be attached and fastened to the nut which in this case is the girder.

2- Ball Bearing End-trucks: these trucks will move along a rail using ball bearings as drivers. The rails will be a stainless steel shafts providing that friction will not be of any importance.

3- DC mounted motor: the motor converts electrical energy to mechanical energy in the form of rotational motion.

With the help of these parts, the girder will be able to move along the x-axis quickly and precisely at the same time. Also, the constraints between the end-trucks and the rails will be highly appropriate with financial design aspects.

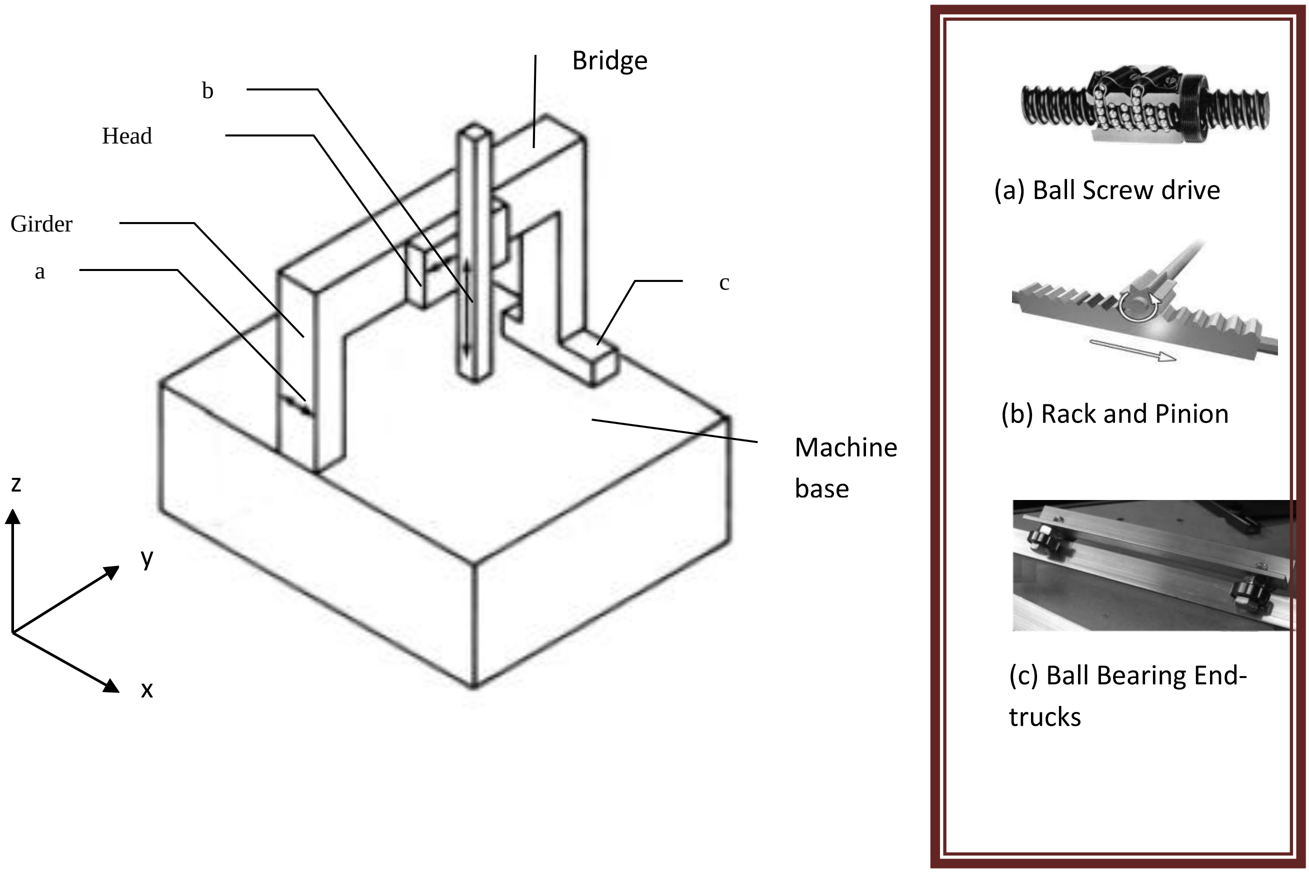
2.2.3 Y-axis Assembly:

The y-axis assembly will consist of a ball screw drive, ball bearing end trucks moving along rails, and a DC mounted motor exactly as the x-axis assembly. In this case, the movement will be asserted to the head which will be moving along the y-axis bridge. Precise motions of the head along the y-axis as well as appropriate speed are important factors that can be attained. But a more important factor in this design is the reduction in mechanical vibration.

2.2.4 Z-axis Assembly:

The z-axis components which hold the laser probe and enable it to move up and down are the Pinion and Rack. In the pinion and rack mechanism, the probe will be attached to the rack which is the translating part with a stationary pinion that rotates in order to make the rack translate. Precision in this case is not of great importance (±1 mm tolerance). The important thing that is achieved is the robust stable movement brought by mechanical design structure of the gear-rack resulting in no need for excessive electronic damping. The pinion in this case will be tied up with a DC motor that will provide it with the rotational movement wanted.

The pinion and rack mechanism will be stationed on the head and the rack will move a perpendicular movement with respect to it. At the bottom of the rack, the laser probe will be mounted in order for it to move along the z-axis. The z-axis assembly is therefore held by the bridge which represents the y-axis assembly. In addition, the bridge will be held by the girder which is the z-axis assembly. This concludes that the z-axis assembly will depend on both the y-axis and x-axis assemblies.



(a) Ball Screw drive

(b) Rack and Pinion

(c) Ball Bearing End-trucks

Fig. 2.1 Physical Structure of Laser CMM

2.3 Dynamic behavior:

By taking first physical principles and interpreting them into dynamic equations, we will be able to obtain a systems mathematical model. Looking at the figure below (which is a loaded ball screw drive schematic) we can envision the dynamic realization of a part of the system. Based on this schematic, we can use the relations we have learned in order to relate between the different variables.

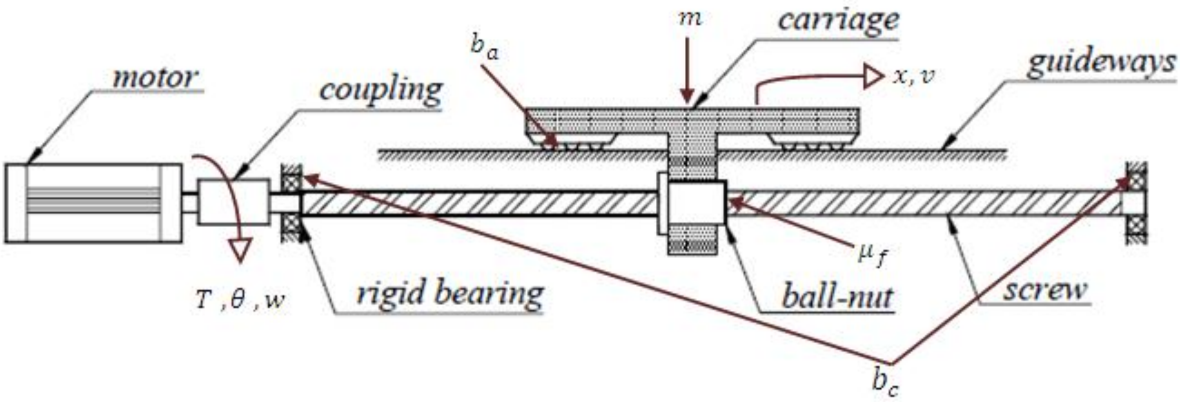


Fig. 2.2 Schematic of loaded ball screw drive (9)

Ball screw dynamic analysis:

The figure above represents one of the most important mechanisms in this project. This mechanism composes of the motor attached to a ball screw rotating lightly via rigid bearings. The nut on the screw supports the carriage of the machine which is the girder in our case. Our duty is to find the nature of this motion which will be done below.

The torque required to move the screw itself can be shown mathematically by the following equation (which is the torque required to raise the load):

$$T = F\left[\frac{l+\pi\,\mu_f\,d_m}{(\pi d_m-\mu_f\,l)}\right] * \frac{d_m}{2}\ \text{(N.m)}\ (10) \qquad (2\text{-}1)$$

Where:

F: is the total force to be moved by the screw (N)

d_m: mean diameter of the screw $(d_m = d - p/2)$ (m)

d: major diameter of screw (m)

p: pitch of screw (m)

l: lead $(l = np \text{ where } n = 1)$ (m)

μ_f : is the coefficient of friction between the screw and nut

Through this equation we can find the torque required to move the screw at any force we require while taking into account all the variables that affect this torque. Neglecting any of these variables will generate an error enlarging the difference between the theoretical and experimental results.

Now by calculating the total kinetic energy of the system we can acquire the equivalent linear inertia reflected at x as shown:

$$½\, j_m\, \omega^2 + ½\, j_s\, \omega^2 + ½ m v^2 = ½ m_{eq} v^2 \tag{2-2}$$

Where j_m and j_s are the moments of inertia of the motor and screw respectively (kg.m^2), m is the mass of the carriage (girder), v and ω are the linear and angular velocities respectively (m/s and rad/s), and m_{eq} is the equivalent mass.

But we clearly understand the relationship between the linear and angular displacement thus leading us to observe the relation between the linear and angular velocities by differentiating the displacement variable with respect to time.

$$x(t) = (\, l/2\pi) \, * \, \theta(t) \tag{a}$$

$$v(t) = (\, l/2\pi) \, * \, \omega(t) \tag{b}$$

By substituting (a) and (b) in equation (2-9) and simplifying it we will attain:

$$m_{eq} \quad = \, (\frac{4\pi^2}{l^2})(\, j_m + j_s \quad) + m \tag{2-3}$$

We can now use m_{eq} in order to find the force of the load based on Newton’s second law:

$$F_{total}(t) \; = \; m_{eq}\, \ddot{x} \tag{2-4}$$

By substituting (a) in (2-11):

$$F_{total}(t) = m_{eq}(\,\frac{l}{2\pi}\ddot{\theta}) \tag{2-5}$$

Since F_{total} is initiated, we can substitute it in the torque equation (2-1) in order to obtain the following equation:

$$T(t) = \left(\frac{d_m}{2}\right)[(\frac{2\pi}{l})\,(j_m + \, j_s) \; + \; \frac{ml}{2\pi}][\frac{l+\pi\, \mu_f d_m}{\pi\, d_m - \mu_f\, l}]\ddot{\theta} \tag{2-6}$$

As for the friction between the carriage and the rails, the opposing force produced is denoted T_{01}. Also the friction produced by the bearings will be denoted T_{02}. Both opposing forces will add up with the torque produced by the screw to obtain T_{eq} which is the equivalent torque.

$$T_{01}(t) = (\frac{l}{2\pi})\, b_a \dot{\theta} \tag{2-7a}$$

$$T_{02}(t) = b_c \dot{\theta} \tag{2-7b}$$

$$T_{eq}(t) = T(t) + T_{01}(t) + T_{02}(t) \tag{2-8}$$

Where b_a and b_c are the coefficient of viscous friction (N.s/m) due to the sliding motion on the rails and the friction of the bearings respectively.

The equivalent torque generate in (2-1) can be used for both x-axis and the y-axis assemblies since both of them have the same design aspects. The values of the parameters will not be the same for both of these assemblies though. Note that equation (2-1) is a second order differential equation relating the variables with respect to time.

Rack and Pinion Dynamic analysis:

The rack and pinion mechanism can be mathematically analyzed and modeled based on the figure below. As seen in the figure below, the input fed to the pinion is torque and the output is angular displacement and its derivatives with respect to time.

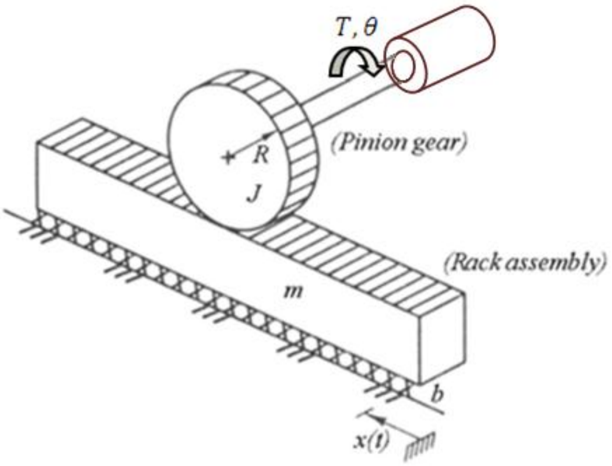


Fig. 2.3 Schematic of the rack and pinion (11)

According to Newtons second law:

$$\sum F = ma$$

$$F(t) - F_0(t) = m * r\ddot{\theta} \qquad (2\text{-}9)$$

Where a is the acceleration (m/s^2) and r is the radius of the pinion (m)

But concerning the friction force between the rack and the pinion, it will be expressed as:

$$F_0(t) = br\dot{\theta} \qquad (2\text{-}10)$$

Substituting (2-10) into (2-9) will result in the subsequent equation:

$$F(t) \ = mr\ddot{\theta} + br\dot{\theta} \tag{2-11}$$

In order for us to find the torque, we must use the next equation and then substitute in it equation (2-10) so that we can describe the torque using all the different forces.

$$\sum T = j\,\ddot{\theta} \tag{2-12}$$

$$T - F * r \ = j\ddot{\theta} \tag{2-13}$$

$$T(t) = (j_g + j_m + mr^2)\ddot{\theta} + br^2\dot{\theta} \tag{2-14}$$

Where j_m and j_g are the moments of inertia of the motor and pinion respectively (kg.m^2), and m is the mass of the rack and its compliances

Now that the mathematical models of the ball screw (2-8) and the "rack and pinion" (2-14) are found, we can describe them in the following matrices:

$$\begin{bmatrix} \left(\frac{d_{m1}}{2}\right)\left[\left(\frac{2\pi}{l_1}\right)(j_{m1} + j_{s1}) + \frac{m_1 l_1}{2\pi}\right]\left[\frac{l_1 + \pi\,\mu_f d_{m1}}{\pi\, d_{m1} - \mu_f l_1}\right] \\ \left(\frac{d_{m2}}{2}\right)\left[\left(\frac{2\pi}{l_2}\right)(j_{m2} + j_{s2}) + \frac{m_2 l_2}{2\pi}\right]\left[\frac{l_2 + \pi\,\mu_f d_{m2}}{\pi\, d_{m2} - \mu_f l_2}\right] \\ (j_g + j_{m3} + m_3 r^2) \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \\ \ddot{\theta}_3 \end{bmatrix} + \begin{bmatrix} \left(\frac{l}{2\pi}\right) b_{a1} + b_{c1} \\ \left(\frac{l}{2\pi}\right) b_{a2} + b_{c2} \\ b_3 r^2 \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} \tag{2-15}$$

Where: T_1 ,T_2 and T_3 are expressed in N.m

It should be clear that all three subsystems are decoupled and entirely do not depend on each other. This is shown by the independent numbering of the variables shown in the subsystems.

Motor Equation:

As I have stated before, so far we have only modeled the mechanism neglecting the motor equation. Clearly now, a wider more efficient look at the system must be conducted.

First of all, the basic understanding of the motor internal components is expressed in figure (3-2). Through using the voltage divider rule we will obtain the following equation:

$$v_{\mathrm{m}} = R_{\mathrm{a}} i + L_{\mathrm{a}} \frac{\partial i}{\partial t} + v \tag{2-16}$$

Where v_{m} is the input voltage (v)

R_a is the armature resistance (Ω)

L_a is the armature inductance (henry)

i is the total current flow(Amps)

v is the back emf (v)

Also, we can relate between v and θ using this equation:

$$v = k_e\dot{\theta} \tag{2-17}$$

Where k_e is the induction coefficient of the motor armature windings (v.s/rad)

By substituting equation (2-24) into (2-23) we will obtain:

$$v_\mathrm{m} = R_\mathrm{a}i + L_\mathrm{a}\frac{\partial i}{\partial t} + k_e\dot{\theta} \tag{2-18}$$

Rearranging the equation will produce:

$$\frac{\partial i}{\partial t} = \frac{v_\mathrm{m} - R_\mathrm{a}i - k_e\dot{\theta}}{L_\mathrm{a}} \tag{2-19}$$

This differential equation represents the mathematical model of the motor relating between the input voltage, the current change, and the change in angular velocity. For every subsystem, due to the decoupling mode, we will need three equations each with different variable values.

2.4 Re-evaluating the Physical System:

Analyzing the physical system, we find that the differential equation that describes the screw takes into account only the rising of the nut. This is because while the screw is in a horizontal position, the difference between the raising and lowering of the nut is negligible (very small). Also, as stated above, the friction between the bearings and the rail where modeled mathematically with prior knowledge that lubrication is found between the bearing and the rail. Furthermore, the dynamic system is considered unstable until feedback is put into the system. This analysis is well fit for this system and describes the LBCMM’s motion from a simple point of view so that everything is clearly stated.

Chapter Three 3

Sensors and Actuators

3.1 Overview:

Sensor and actuators are essential components of a closed loop system. These components are used to progress (actuate) and measure the wanted system or subsystem. A sensor can be legitimately defined as a device that produces an output signal for the purpose of sensing of a physical phenomenon. It converts a signal from one physical form to a corresponding signal, which has a different physical form. This phenomenon in our case can be sent to the computer for processing. As for the actuators, they can be defined as the muscle behind a mechatronics system that accepts a control command (mostly in the form of an electrical signal) and produces a change in the physical system by generating force, motion, heat, flow, etc.

3.2 Actuators:

The movement of the whole CMM depends on the actuators used. For this movement to be appropriate and precise, actuator selection should be considered deeply. Furthermore, the selection should take into account the relations or connections with other components and devices. This will give us an actuating unit comprising the actuator, power supply, and the coupling mechanism (shown in Fig 3.1). This concludes that the integration of appropriate devices and components will lead to a robust design with outstanding results.

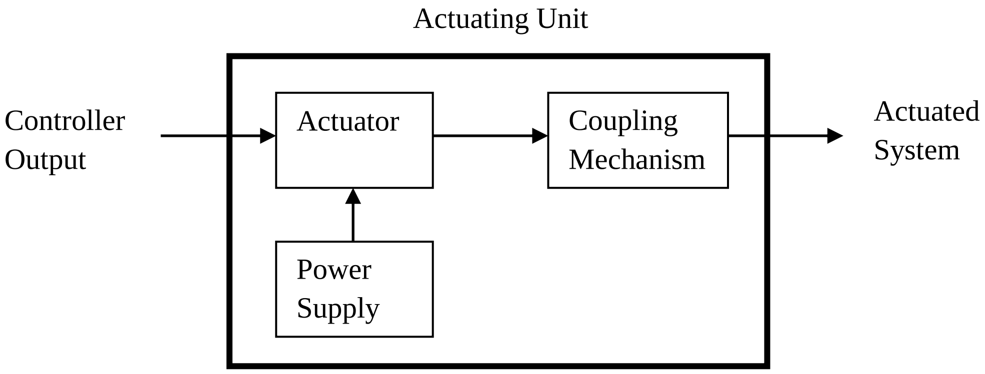


Fig 3.1 Typical Actuating Unit

3.2.1 Electromechanical Actuators (Motors):

Motors are machines that convert electrical energy into mechanical energy in the form of rotation in order to produce the torque required for movement. Motors are classified into three categories, AC, DC, and stepper motors. DC motors are advantageous in the case of "ease of control" where varying the voltage leads to change in speed. The governing mechanical equation of the DC motor according to Newton's second law can be written as:

$$T = J\frac{\partial \omega}{\partial t} + T\mathrm{L} + T\mathrm{Loss} \qquad (3\text{-}1)$$

Where T is torque (N.m)

J is the total inertia

ω is the angular mechanical speed of the rotor

TL is the torque applied to the motor shaft

TLoss is the internal mechanical losses(damping)

DC motors are also classified into brushed and brushless. In this project, the choice that is seen appropriate includes the use of DC brushed motors. This choice was made for the following reasons:

- It is inexpensive compared to the brushed DC motor
- It can reach to moderate speeds with high-end torque
- It needs a simple drive for running
- It is fully applicable for velocity control and high speed position control

The DC motor in this project will carry out the translational motion on the three axes. This means that the power of each motor will be calculated with respect to the forces exerted on each motor (weight, or dynamic forces) with an additional factor of safety. This can be calculated by the equation:

$$P = T\omega = vI \qquad (3\text{-}2)$$

Where v is armature voltage (volts)

I is electrical current (ampere)

The voltage can be calculated by using the voltage divider rule on the figure shown below. This figure is a schematic of a conventional DC motor with loading.

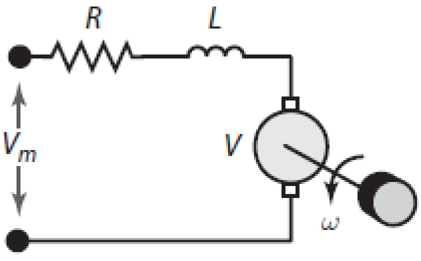


Fig 3.2 Conventional DC Motor with Loading

When an input voltage (v_{m}) is applied to the armature, by taking into account the inductance and the resistance of the motor, we will obtain the armature voltage. This is shown in the following equation:

$$v_{\mathrm{m}} = R_{\mathrm{a}} i + L_{\mathrm{a}} \frac{\partial i}{\partial t} + v \tag{3-3}$$

By using the mechanical equation in order to find the torque and the voltage divider in order to find the armature voltage, we can interplay with the other factors to find the power desired. The factors (which are the speed and the electrical current) required are set to meet the designer's desire.

An electromechanical actuating unit can be profound as shown below in Fig. 3.3. The actuating unit contains the power supply, electrical actuating unit, motor, and coupling mechanism. The electrical actuating unit and the motor together are considered the actuator in this case. This unit will receive commands from the controller so that the actuated mechanisms (which are in this case the ball screw drive and the rack and pinion) take out the tasks required (which is motion in this case).

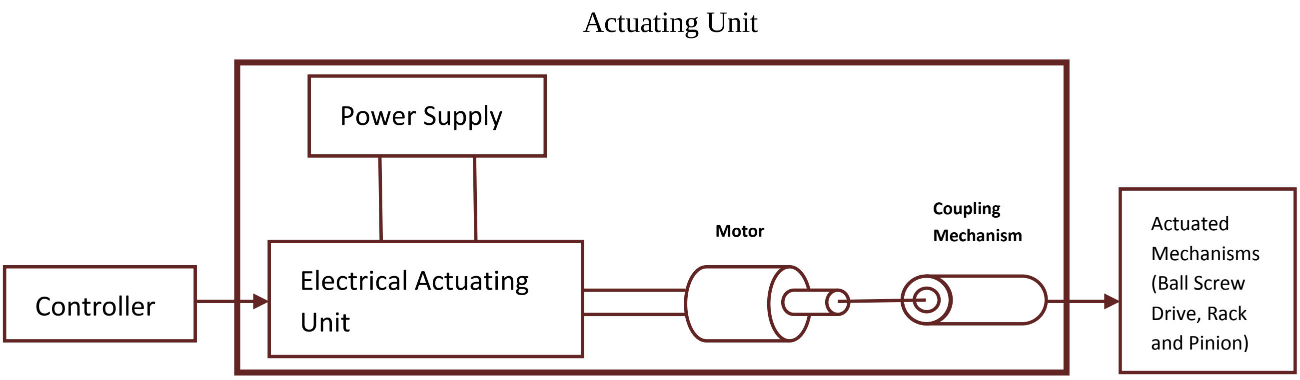


Fig 3.3 Electromechanical Actuating Unit

3.2.2 Electrical Actuators:

The electrical actuators are mainly described by logical on/off functions. Such actuators that will be used in the project are switches, transistors, MOSFETs, and a H-bridge. These devices accept a low energy level command signal from the controller and switch the motor on/off. A typical electrical actuating unit is shown below (Fig 3.4). This unit's components are the power supply, a NPN transistor, and a solid state relay. The unit will receive an on/off signal from the controller and will result in actuating a system by sending an electric current to the load (which is the motor in this case).

Actuated unit

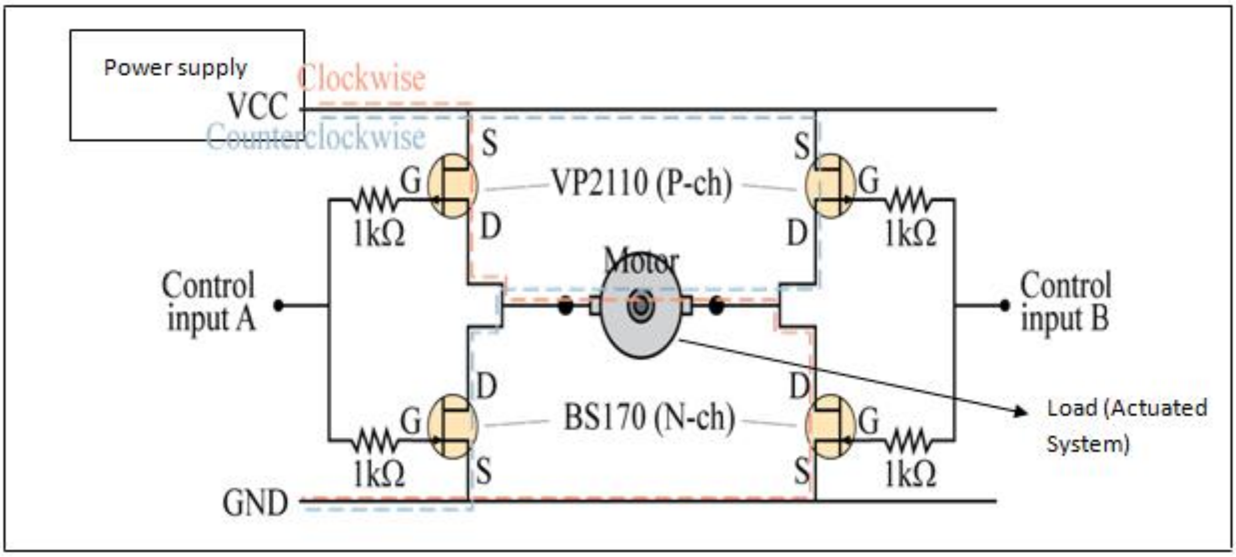


Fig 3.4 Electrical Actuating Unit (12)

3.2.3 Actuated Mechanisms:

Actuator units receive commands and produce forces that create changes in the physical system. The changes in the physical system in this project will be through the actuated mechanisms coupled with the actuators. These actuated mechanisms are the ball screw drive and the “rack and pinion”. These two mechanisms handle the overall movement of the CMM. They convert the rotational force received from the motor into a linear force. This categorizes these mechanisms as mechanical transducers. These transducers will be described below.

1- Ball Screw Drive*:*

A ball screw drive mechanism is a mechanical transducer that converts the rotational motion of the screw to linear motion conducted by the nut which is held. They are perhaps the most common type of lead screws used in industrial machinery and precision machines. This mechanism moves with relatively small friction compared to other types of lead screws where friction may be neglected for this reason. Also, backlash problems are eliminated; which results in highly accurate movement with very small (neglected) error. Furthermore, efficiency is very high (sometimes exceeding ninety percent) which assures that power consumption is very low. Below in Fig. 3.5 is a schematic of a ball screw drive system coupled to a motor and holding a carriage. In our case, the carriage held by the nut is the girder.

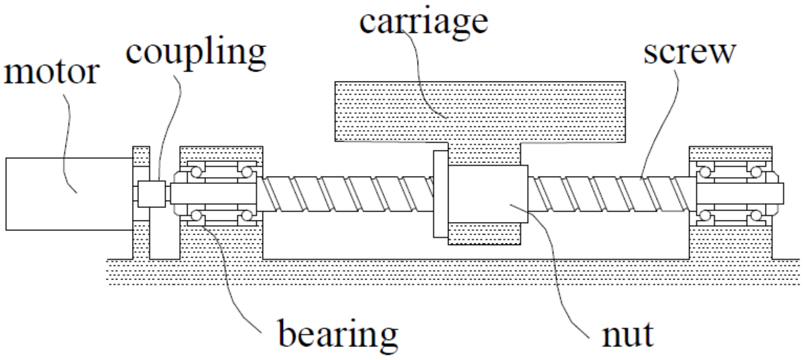


Fig 3.5 Schematic of Ball screw drive unit

2- Rack and Pinion*:*
The rack and pinion mechanism is a mechanical transducer that converts rotational motion into linear motion by a pair of gears. The pinion is the stationary rotating component connected to the electromechanical actuator and the rack is the linear translating component carrying the laser interferometer. The rack and pinion mechanism is illustrated in fig 2.1.

3.2.4 Power Supply:

The CMM subsystems need a power in order for them to operate. This power can be supplied to meet the needs of the subsystems accordingly. First of all, the actuators we intend to operate are 24 volt DC brushed motors with a power rating of 48 watts. This means that a transformer will be needed for stepping down the voltage from (220 volts) from the plug to 24 volts to the motor. The winding ratio between the primary and secondary windings will be approximately 8:1. The secondary voltage will be 27.5 volts from this transformer step down ratio. But now we need to convert the ac oscillating voltage to dc line voltage. This can be done by the bridge rectifier circuit that will convert ac to dc and consume a small amount of voltage approximately 1.4 volts. The power supply schematic is shown below.

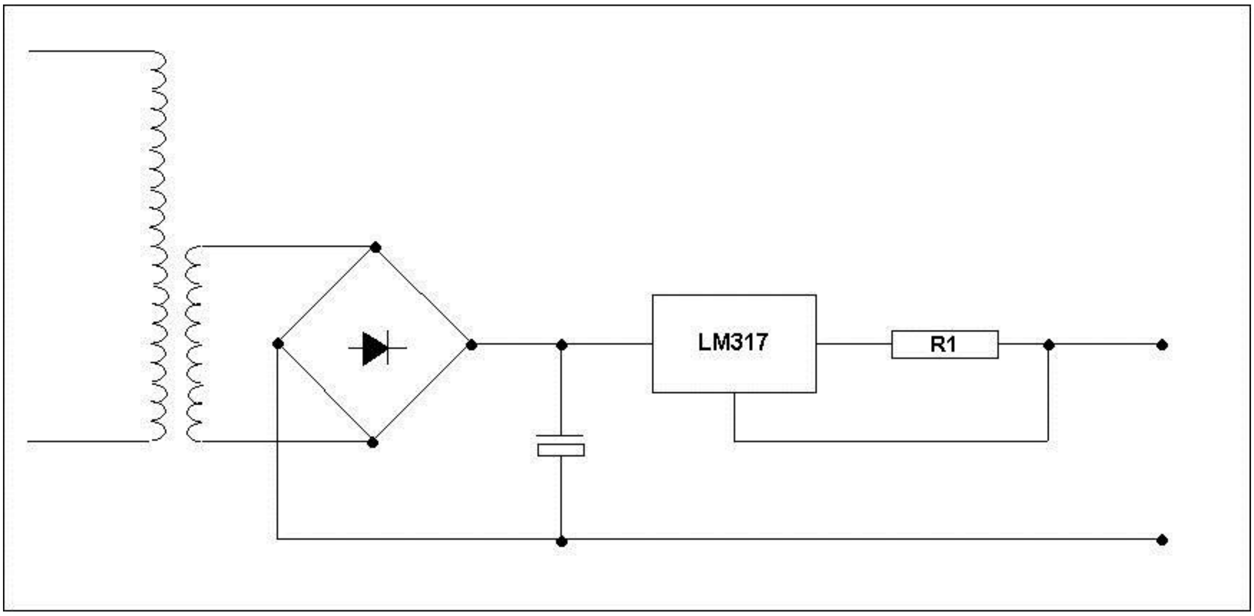


Fig 3.6 Power supply unit

3.3 Sensors:

3.3.1 Digital Transducer (Shaft Encoder):

Digital transducers are measuring devices (sensors) that produce digital feedback interpreting output measurement values. A shaft encoder is considered a digital transducer that is used to measure angular velocity and displacement by generating a digital reading. The shaft encoder is relatively advantageous in many aspects. Some of these advantages are:

1. High resolution(number of pulses per revolution and number of bits output)
2. High accuracy(immune to noise interference with accurate digital pulsing)
3. Digital system compatibility, ease of use, relatively low cost, and reliable

Shaft encoders are classified into two categories, incremental and absolute. The incremental encoder uses a rotating transducer disk to output digital pulses as a result of rotational motion. These pulses can be used to indicate the displacement with respect to a reference point. Absolute encoders on the other hand have many pulse tracks on their transducer disks.

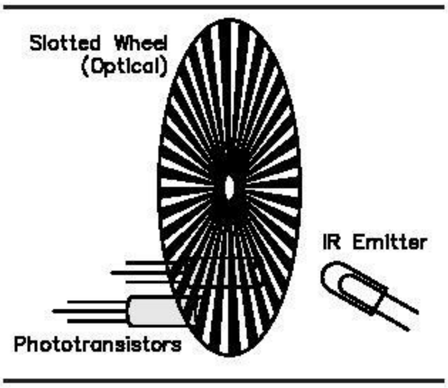


Fig 3.7 Optical encoder internal components

Signal generation can be obtained through many different methods. The most important, cost effective and popular method is the optical method. The optical encoder uses an opaque disk that has one or more circular tracks, with transparent windows slotted in each track. A parallel beam of light is projected to all tracks from one side of the disk. The transmitted light is received by photo sensors on the other side of the disk. This is shown in Fig 3.7 which indicates just one track and one receiver.

There are two configurations for an incremental encoder disk. These configurations are either the offset sensor configuration or the offset track configuration. The offset sensor configuration is shown in the figure below. Both of these configurations are done so that we can differentiate between clockwise and counterclockwise rotation.

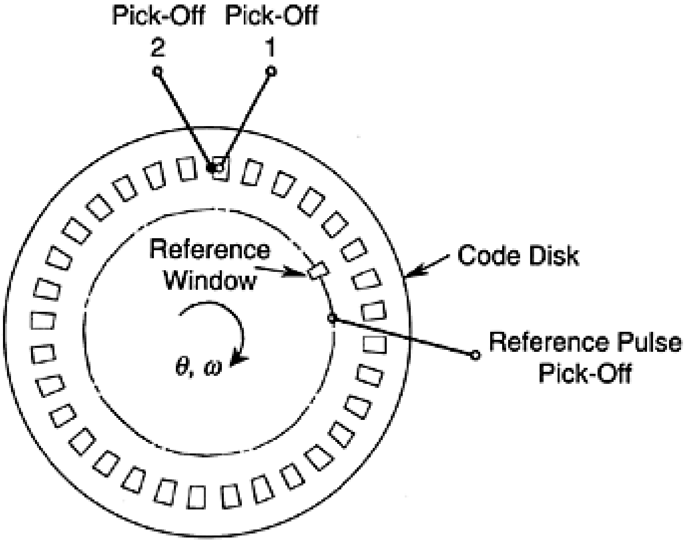


Fig 3.8 Offset sensor configuration (13)

As shown in Fig. 3.9, if v_1 lags v_2 by a quarter of a cycle then the rotation can be stated clockwise. Otherwise, if $v_1$leads v_2 by a quarter of a cycle, then the rotation will be counterclockwise. Hence, the direction of rotation can be obtained by determining the phase difference of the two output signals, using phase-detecting circuitry or software.

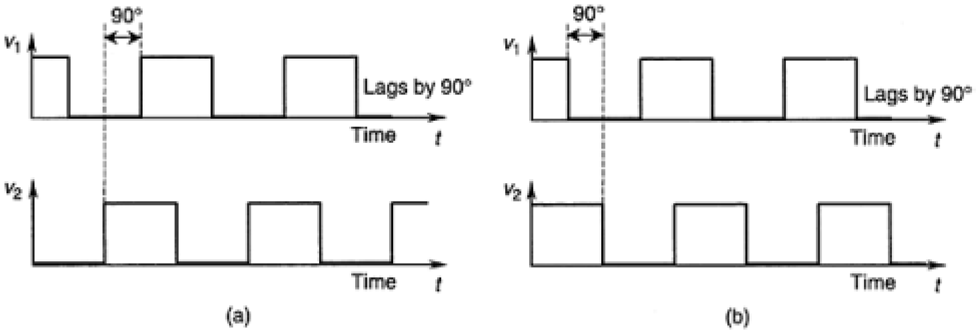


Fig 3.9 (a) $v_1$lags v_2 clockwise (b) $v_1$leads v_2 counterclockwise(13)

3.3.2 Potentiometers

A potentiometer is a three-terminal resistor with a sliding contact that forms an adjustable voltage divider. Potentiometers are commonly used to control electrical devices such as volume controls on audio equipment.

One potentiometer is needed to be fixed on the motor shaft in order to measure the link positions. If a sudden energy loss happens, the system will identify these positions immediately when power turns on i.e. the potentiometer may be considered as an absolute sensor.(14)

Fig 3.10 Potentiometer sensor

3.3.3 Limit switches:

A limit switch is used to limit the activation of an electrical circuit. When a circuit is “closed,” it allows the flow of electrical current through the switch to pass to the device being powered. When the switch is “open,” the switch is disengaged and no electrical power will pass through it. Whether the limit switch is open or closed is generally determined either by the position of a device being powered or by a set amount of time a device requires to complete a specific task. (15)

The most common type of limit switch is a mechanical limit switch. This switch tracks the location of a specific item and opens or closes when that item reaches a specific location. The switch is activated by physical contact, or lack thereof.

In this project two limit switches are needed, one of the switches fixed at the beginning of the X-axis beam, and another fixed at the beginning of the Y-axis beam. This is needed for homing or referencing the LBCMM (point of reference calibration).

Fig 3.11 Limit switch sensor

3.3.4 Laser Scanning Sensor:

Laser scanning is well suited to developing large point clouds in a short period of time. 3D scanning is a fast and accurate method of putting physical measurements of an object onto the computer in an organized manner. The non-contact nature also allows delicate objects and items to be digitized as well. In this project, we will use a laser sensor to measure the z-axis. Its working principle will be built on laser triangulation. It is a professional method for noncontact position sensing. The sensor most likely to be used will be a miniaturized optoNCDT 1302 laser sensor with very advanced features. Such features are:

Measuring range: 200mm

Linearity max: 40µm

Resolution max: 4µm

Measuring rate: 750 Hz

Compact design with integrated electronics

Low-cost sensor

Scale able analog output

Trigger input

RS422 interface

Chapter Four 4

Integration, Interfacing, and ControlSystem

4.1 Overview:

One of the most important aspects of mechatronics is the integration between different modules. This is how a mechatronics engineer can work concurrently on a certain task, and at the same time uses his skills to prevent problems from happening. Also, while synergistically integrating between the components, proper interfacing methods can be achieved. Furthermore, this allows the engineer to give every subcomponent its importance throughout controller design. Everything this way will be clear and easy.

4.2 System Modeling:

In this section we will display the main methods of modeling a system. Starting, I will show the information flow using a context diagram to clear up the system operation. Then, I will state out the hardware/software integration.

4.2.1 Information Flow:

If we want to model the Laser Bridge CMM, we must understand the main functions of this machine. For this point, I will use a context diagram focusing attention on information flows that must exist to enable us to point out scenarios of different cases in the machines operations.

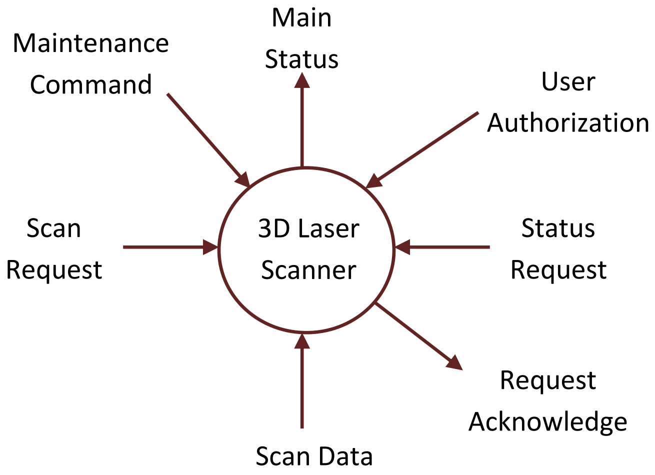


Fig 4.1 Context diagram of the LBCMM

Now for the Laser CMM to scan data, appropriate movement commands must be addressed. This means that the user interfacing this machine must input the starting position of the scanning device and the position of completion in addition to the speed for desired resolution. Also, according to the figure above, the user must also give authorization, status request, maintenance command, and scan request. In return, the machine will supply us with its main status and acknowledge the command set by the user. This can all be done by integrating between the components then software programming the status and command functions of these components. This will lead us to hardware/software integration.

4.2.2 Hardware/Software Integration:

The hardware and software integration is an essential part of this project. As we move forward towards building this project, we must understand the hardware's classification, organization, and placement so that we can make appropriate control software capable of realizing all the components respectively. As shown in the figure below, the hardware that will be used in this project are the PIC microcontroller, motor drive, DC brushed motor, ball screw drive(or rack and pinion), incremental encoder, and the laser triangulation sensor. As for the software, the computer will use certain programmed software, as well as the microcontroller, in order to send out control commands and receive and process signals. With robust machine building and an intelligent well programmed software, the CMM will work accurately and efficiently with relatively high speed and high resolution.

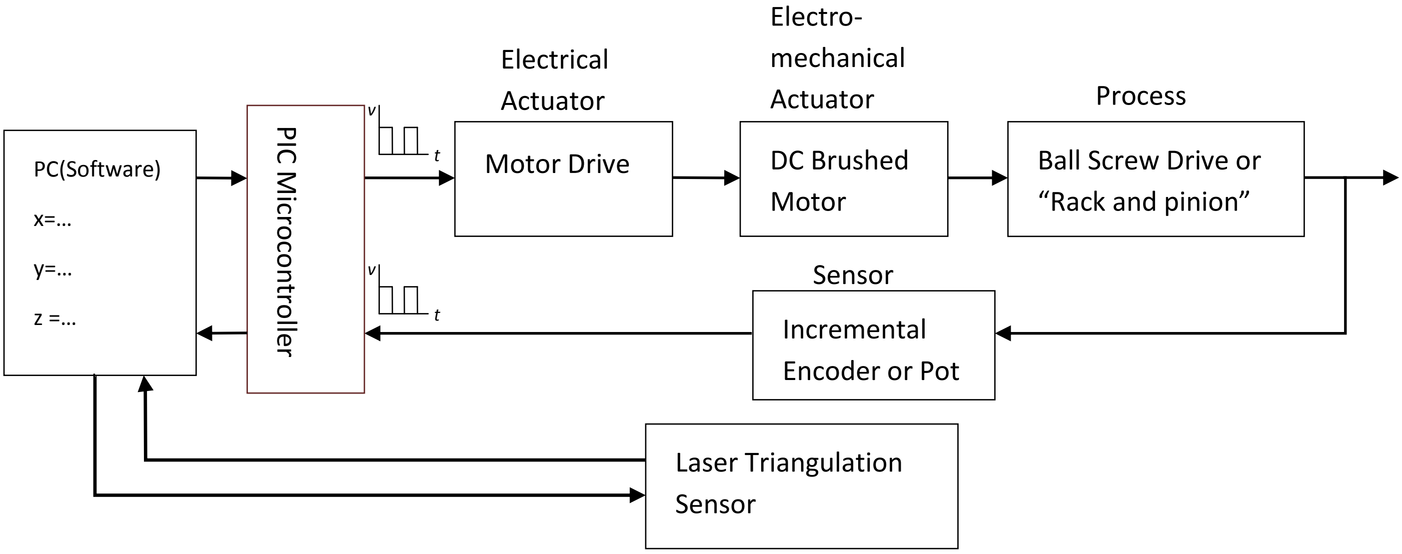


Fig 4.2 Hardware/Software integration block diagram

4.3 System Control:

Throughout this section, all three subsystems that move the probe in the x, y, and z axis will be put together in a state space matrix. This way, we can convert the state space model into transfer functions. Also, we will test controllability and observability so that we can design an efficient controller. Last of all, the overall results will be simulated and compared.

4.3.1 System State Space Representation:

As we have seen in the dynamic physical modeling in chapter 2, we were able to relate between$T$ and θ(in both the ball screw and 'rack and pinion') and we also were able to obtain a differential equation modeling the motor. Now that these equations are ready, we can choose the states that represent our system. First of all, let's put down all the equations to find the representing state variables.

$$T_1(t) = \left(\frac{d_{m1}}{2}\right)\left[\left(\frac{2\pi}{l_1}\right)(j_{m1} + j_{s1}) + \frac{m_1 l_1}{2\pi}\right]\left[\frac{l_1 + \pi\mu_f d_m}{\pi d_m - \mu_f l_1}\right]\ddot{\theta}_1 + \left[\left(\frac{l}{2\pi}\right)b_{a1} + b_{c1}\right]\dot{\theta}_1$$

$$T_2(t) = \left(\frac{d_{m2}}{2}\right)[(\frac{2\pi}{l_2})(j_{m2} + j_{s2}) + \frac{m_2 l_2}{2\pi}]\left[\frac{l_2 + \pi\mu_f d_m}{\pi d_m - \mu_f l_2}\right]\ddot{\theta}_2 + \left[\left(\frac{l}{2\pi}\right)b_{a2} + b_{c2}\right]\dot{\theta}_2$$

$$T_3(t) = (j_g + j_{m3} + m_3 r^2)\ddot{\theta}_3 + [b_3 r^2]\dot{\theta}_3$$

The torque can be represented by the following equation:

$$T = K_a * i \tag{4-1}$$

Where K_a is the motor torque constant (N.m/A)

Substituting equation (4-1) into the previously written differential equations and rearranging will give us:

$$\ddot{\theta}_1 = \frac{K_{a1} * i_1 - \left[\left(\frac{l}{2\pi}\right)b_{a1} + b_{c1}\right]\dot{\theta}_1}{\left(\frac{d_{m1}}{2}\right)\left[\left(\frac{2\pi}{l_1}\right)(j_{m1} + j_{s1}) + \frac{m_1 l_1}{2\pi}\right]\left[\frac{l_1 + \pi\mu_f d_{m1}}{\pi d_{m1} - \mu_f l_1}\right]} = \frac{K_{a1} * i_1 - \left[\left(\frac{l}{2\pi}\right)b_{a1} + b_{c1}\right]\dot{\theta}_1}{R_1} \tag{4-2}$$

$$\ddot{\theta}_2 = \frac{K_{a2} * i_2 - \left[\left(\frac{l}{2\pi}\right)b_{a2} + b_{c2}\right]\dot{\theta}_2}{\left(\frac{d_{m2}}{2}\right)[(\frac{2\pi}{l_2})(j_{m2} + j_{s2}) + \frac{m_2 l_2}{2\pi}]\left[\frac{l_2 + \pi\mu_f d_{m2}}{\pi d_{m2} - \mu_f l_2}\right]} = \frac{K_{a2} * i_2 - \left[\left(\frac{l}{2\pi}\right)b_{a2} + b_{c2}\right]\dot{\theta}_2}{R_2} \tag{4-3}$$

$$\ddot{\theta}_3 = \frac{K_{a3} * i_3 - [b_3 r^2]\dot{\theta}_3}{(j_g + j_{m3} + m_3 r^2)} = \frac{K_{a3} * i_3 - [b_3 r^2]\dot{\theta}_3}{R_3} \tag{4-4}$$

Where:

$$R_1 = \left(\frac{d_{m1}}{2}\right)\left[\left(\frac{2\pi}{l_1}\right)(j_{m1} + j_{s1}) + \frac{m_1 l_1}{2\pi}\right]\left[\frac{l_1 + \pi\mu_f d_{m1}}{\pi d_{m1} - \mu_f l_1}\right]$$

$$R_2 = \left(\frac{d_{m2}}{2}\right)[(\frac{2\pi}{l_2})(j_{m2} + j_{s2}) + \frac{m_2 l_2}{2\pi}]\left[\frac{l_2 + \pi\mu_f d_{m2}}{\pi d_{m2} - \mu_f l_2}\right]$$

$$R_3 = (j_g + j_{m3} + m_3 r^2)$$

As for the motor equations (found at chapter 2 equation (2-19)), they are represented as the following:

$$\frac{\partial i_1}{\partial t} = \frac{v_{\mathrm{m1}} - R_{\mathrm{a1}} i_1 - k_{e1}\dot{\theta}_1}{L_{\mathrm{a1}}} \tag{4-5}$$

$$\frac{\partial i_2}{\partial t} = \frac{v_{\mathrm{m2}} - R_{\mathrm{a2}} i_2 - k_{e2}\dot{\theta}_2}{L_{\mathrm{a2}}} \tag{4-6}$$

$$\frac{\partial i_3}{\partial t} = \frac{v_{\mathrm{m3}} - R_{\mathrm{a3}} i_3 - k_{e3}\dot{\theta}_3}{L_{\mathrm{a3}}} \tag{4-7}$$

By taking a look at the equations from (4-2) to (4-7), we can see that we have a 9th order state vector defined as:

$$\vec{x} = [x_1 x_2 x_3 x_4 x_5 x_6 x_7 x_8 x_9]^T = \left[i_1 i_2 i_3 \theta_1 \dot{\theta}_1 \theta_2 \dot{\theta}_2 \theta_3 \dot{\theta}_3\right]^T \tag{4-8}$$

As for the input signals, we will have a 3rd order input vector as shown:

$$\vec{u} = [u_1 u_2 u_3]^T = [v_{m1} v_{m2} v_{m3}]^T \tag{4-9}$$

A state differential equation can relate the rate of change of the state of the system to the state of the system and the input signals. The system can be represented by the compact notation of the state differential equation as:

$$\dot{\vec{x}} = A\vec{x} + B\vec{u} \tag{4-10}$$

Where A and B are both matrices of the orders $n \times n$ and $n \times m$ respectively. In our case $n = 9$and $m = 3$. The representation of the state differential equation can now be obtained.

$$\dot{\vec{x}} = \underbrace{\begin{bmatrix} -\frac{R_{\mathrm{a1}}}{L_{\mathrm{a1}}} & 0 & 0 & 0 & -\frac{k_{e1}}{L_{\mathrm{a1}}} & 0 & 0 & 0 & 0 \\ 0 & -\frac{R_{\mathrm{a2}}}{L_{\mathrm{a2}}} & 0 & 0 & 0 & 0 & -\frac{k_{e2}}{L_{\mathrm{a2}}} & 0 & 0 \\ 0 & 0 & -\frac{R_{\mathrm{a3}}}{L_{\mathrm{a3}}} & 0 & 0 & 0 & 0 & 0 & -\frac{k_{e3}}{L_{\mathrm{a3}}} \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ \frac{k_{a1}}{R_1} & 0 & 0 & 0 & -\frac{\left[\left(\frac{l}{2\pi}\right) b_{a1} + b_{c1}\right]}{R_1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & \frac{k_{a2}}{R_2} & 0 & 0 & 0 & 0 & -\frac{\left[\left(\frac{l}{2\pi}\right) b_{a2} + b_{c2}\right]}{R_2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & \frac{k_{a3}}{R_3} & 0 & 0 & 0 & 0 & 0 & -\frac{[b_3 r^2]}{R_3} \end{bmatrix}}_{A_{9\times 9}} \vec{x}$$

$$+\underbrace{\begin{bmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\\0 & 0 & 0\\0 & 0 & 0\\0 & 0 & 0\\0 & 0 & 0\\0 & 0 & 0\\0 & 0 & 0\end{bmatrix}}_{B_{9\times 3}}\vec{u}\text{(4-11)}$$

The outputs of a linear system can also be related to the state variables and the input signals by the output equation:

$$\vec{y} = C\vec{x} + D\vec{u} \qquad \text{(4-12)}$$

Where $\vec{y}$ the set of output signals expressed in column vector form, C is the output matrix and D is a zero matrix since there is no feed forward signal in the system. The output equation is represented as:

$$\vec{y} = \begin{bmatrix}0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0\\0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0\\0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0\end{bmatrix}\vec{x} + [0]\vec{u} \qquad \text{(4-13)}$$

4.3.2 Transfer Function of the System:

In order for us to attain the transfer function of the system, we must operate by converting the state space model into the desired transfer function. This can be done mathematically by the following equation:

$$T(s) = C(SI - A)^{-1}B + D\text{(4-14)}$$

In our case, this will cause complication due to the high order of the matrices. Our alternative to solve this problem is to use the matlab to compute the transfer functions by using the following command:

>>$T = tf(A, B, C, D, 1)$

But in order for the matlab to compute this command, all entries in the matrices must be a numerical value. For us to make the matrices completely numerical, we must substitute the parameters values of the system. These values are shown precisely in fig 2.2 and fig 2.3 and described throughout the equations.

Table 4.1 Parameter values

Parameter Values	
Parameter	Value
d_{m1}, d_{m2}	23mm
l_1, l_2	20mm
j_{m1}, j_{m2}, j_{m3}	0.0192kg.m^2
j_g	0.01 kg.m^2
j_{s1}, j_{s2}	0.00027 kg.m^2
b_{a1}, b_{a2}	0.1 N.s/m
b_{c1}, b_{c2}	0.03 N.m.s/rad
b_3	0.13 N.s/m
m_1	40 kg
m_2	9.5 kg
m_3	1.2 kg
k_{a1}, k_{a2}, k_{a3}	0.5 N.m/A
μ_f	0.1
r	30 mm
$R_{\mathrm{a1}}, R_{\mathrm{a2}}, R_{\mathrm{a3}}$	0.34 Ω
$L_{\mathrm{a1}}, L_{\mathrm{a2}}, L_{\mathrm{a3}}$	0.5mH
k_{e1}, k_{e2}, k_{e3}	0.054 v.s/rad

By substituting the values of the parameters and operating the command mentioned above, the matlab software provided me with six transfer functions. The number of functions matched the number of active outputs in matrix C. The transfer functions will be divided for three decoupled subsystems with the output describing the velocity and position.

$$TF1 = \frac{\theta_1}{v_{\mathrm{m1}}} = \frac{1.799}{S^3+0.79S^2+0.268S}$$

$$TF2 = \frac{\theta_2}{v_{\mathrm{m2}}} = \frac{1.825}{S^3+0.79S^2+0.268S}$$

$$TF3 = \frac{\theta_3}{v_{\mathrm{m3}}} = \frac{15.82}{S^3+0.688S^2+1.715S}$$

4.3.3 System's Stability, Controllability, and Observability:

Clearly from the transfer functions above, we can see that we have a pole at the imaginary axis of multiplicity 1 and the rest of the poles are at the left hand side of the imaginary axis. This means that the system can be called marginally stable. Throughout the stability analysis, we have seen that the system is bounded input bounded output, thus pulling the systems from the marginally stable mode to 'stable'. This concludes that the system will undergo oscillations then after a period of time it will reach stability.

As for controllability, first by finding the controllability matrix which is shown below, then by finding its rank(using Matlab), the system's ability to be controlled was found.

$$M_c = [B \quad AB \quad A^2B \quad A^3B \quad A^4B \quad A^5B \quad A^6B \quad A^7B \quad A^8B] \tag{4-15}$$

>>$M_c = ctrb(A, B)$

>>$R_c = rank(M_c)$

By the results of the commands above, the rank was 9 meaning that it is full rank thus controllable. Observability is also found by attaining the rank of the observability matrix. The observability matrix is shown below.

$$M_o = \begin{bmatrix} C \\ CA \\ CA^2 \\ CA^3 \\ CA^4 \\ CA^5 \\ CA^6 \\ CA^7 \\ CA^8 \end{bmatrix} \tag{4-16}$$

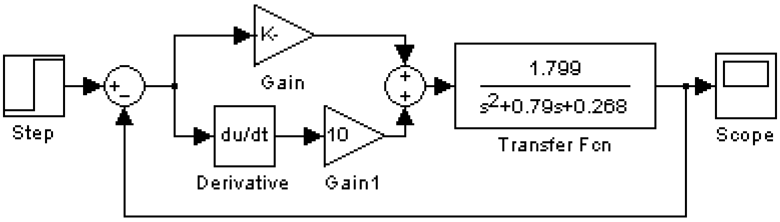
>>$M_o = obsv(A, C)$

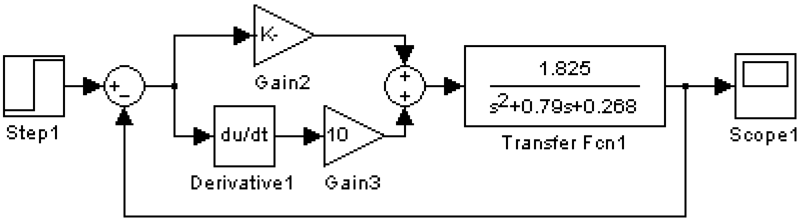
>>$R_o = rank(M_o)$

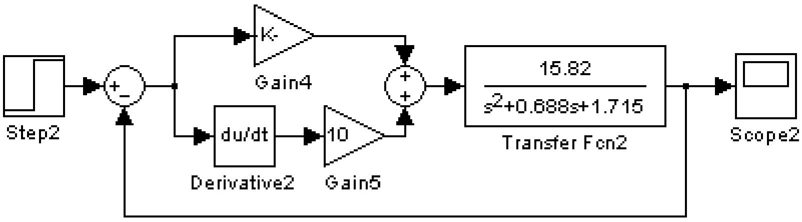
By using the Matlab commands above, the rank of the observability matrix is given 9 (full rank) concluding that the system is observable. It can be stated that the system is stable, controllable, and observable.

4.3.4 Controller Design:

A controller is the device that will optimize the system to its full capabilities. In this project, the controllers used to adjust the system's transient response and overshoot are simply PD controllers. It is a simple way of speeding up the transient response by adding a zero to the forward path. The method used to find the zero is shown below (implemented on the ball screw drive subsystem).







1- Find the dominant poles by choosing the overshoot we desire (dominant poles: $-0.244 \pm 0.255j$ at $\zeta = 0.691$)
2- Find ω_n and the peak time at the dominant poles ($\omega_n = 0.353\ rad/s, T_p = 12.3\ s$)
3- Create a new peak time related with the old one($T_{pN} = 0.41\ s$)
4- Find ω_d for the new peak time ($\omega_d = 7.66$)
5- Find $(\zeta\omega_n)_{new}$ from the following equation $(\zeta\omega_n)_{new} = \frac{\omega_d}{\tan(\theta)}\theta = cos^{-1}(\zeta)$
6- Find the angle of the new zero and its placement ($\theta_z = 3.5$degrees $Z_c = 132.9$)
7- Obtain K_d by finding $\frac{\sum L_{poles}}{\sum L_{zeros}}$ (length of poles over length of zeros)

This is now tested on Matlab Simulink to see the system blocks and their outputs.

4.3.5 Simulation Results:

Simulation is one of the most important parts in system modeling. Through simulation, one can see the results of the system and compare it with other options. This way, optimization through the change in parameters can be conducted for a robust control system design.

Through Matlab software, θ was modeled with respect to time. The result of the simulation on the Matlab software for one of the three subsystems is shown below.

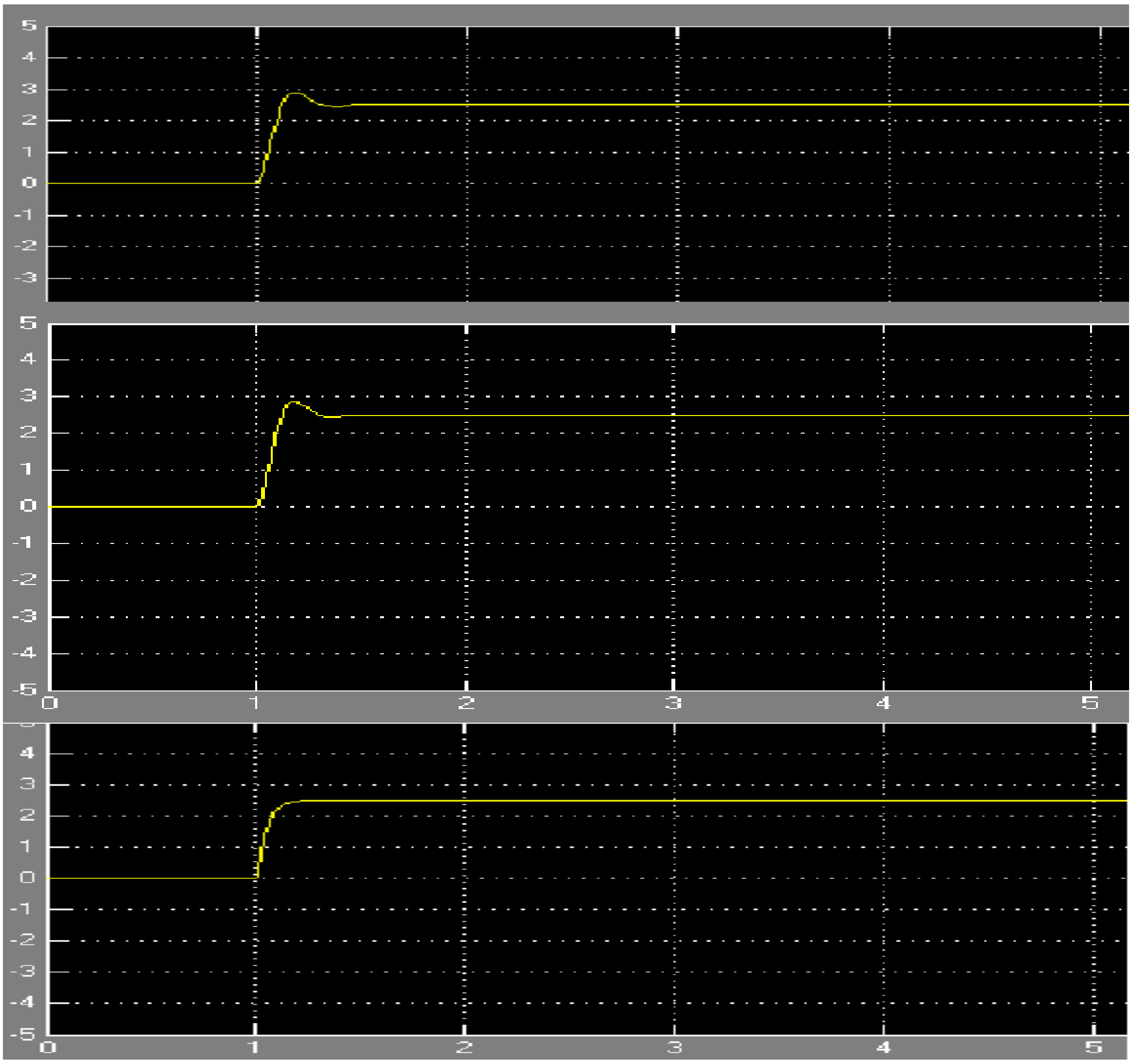


Fig 4.4 simulink result of the transfer functions

the simulation results, we were able to speed up the process by more than a multiplicity of two and at the same time decrease the overshoot to zero. This was done successfully with respect to theoretical capability analysis of the control system and by also partially taking into account the realistic capabilities of the components (actuators in precise).

Chapter Five 5

Alternatives, Solutions, and Results

5.1 Overview:

In order to fulfill the requirements of the project, alternatives and solutions are required to replace expensive or rare parts. These solutions should be fit to replace the main requirements will little defects or disadvantages. The important factor in this chapter is to explain how we used our abilities to solve main problems.

5.2 Alternatives:

As a result of low financial aid and our financial incapability, we had to find alternatives for replacing expensive parts in our project. Some of them were mechanical parts and the others include electronic circuits and a sensor.

5.2.1 Mechanical Alternatives:

The mechanism in the figure below represents a good solution for anti-backlash and a good alternative replacing the ball nut. This mechanism consists of three components, the spring, the nut, and the housed nut which is a nut attached with three bars via welding as shown below. This alternative is very cheap but it has a big disadvantage. This disadvantage is the high friction built by the pressured contact acting between the threads. As the spring is compressed more between the two nuts, the less the backlash and the more the contact friction becomes. So in order to get the best anti-backlash and the least friction, we made an averaged compromise.

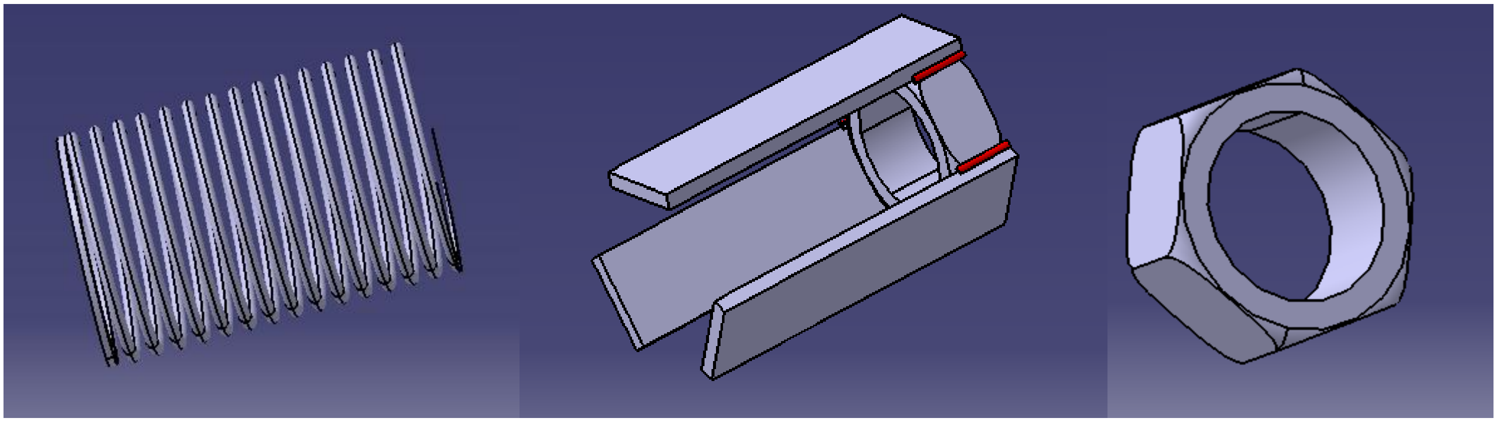


Fig. 5.1 Anti backlash mechanism

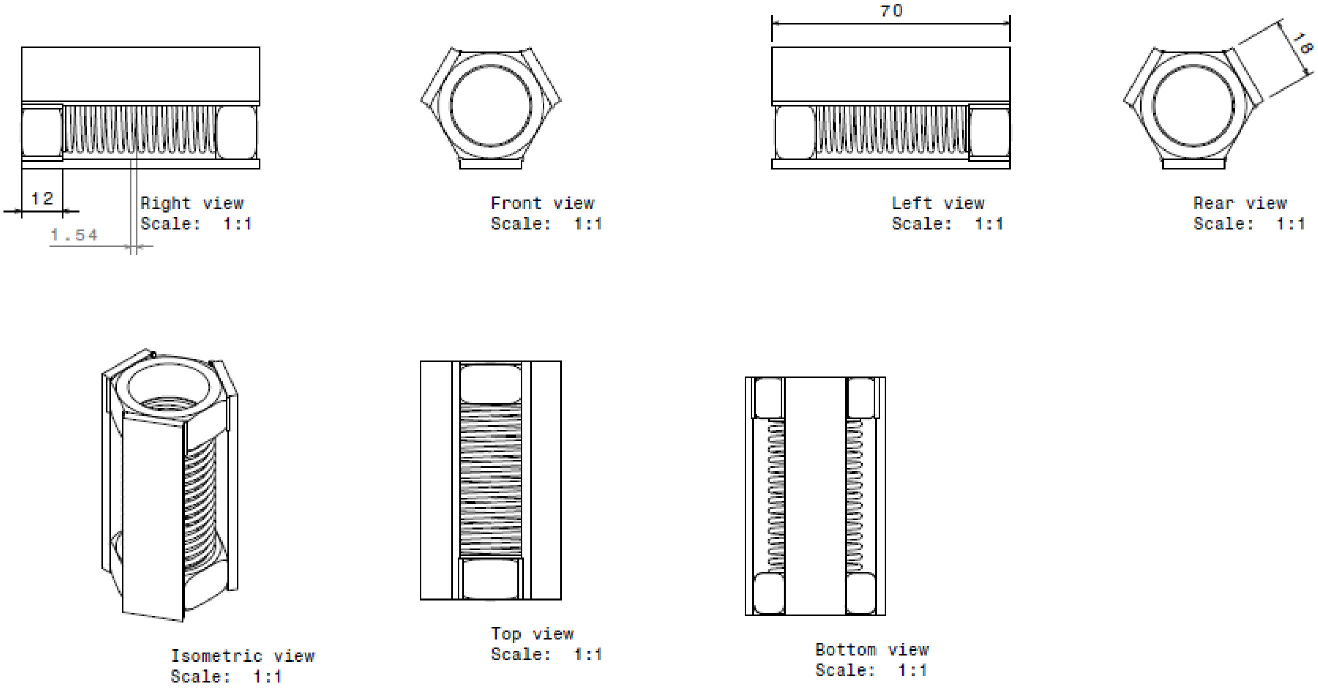


Fig. 5.2 Schematic diagram for anti backlash mechanism

Another mechanism that we worked on was the end-truck mechanism. Instead of buying expensive ball sliders, we worked on machining the end-truck mechanisms for similar use. This end truck, as shown below consists of two ball bearings on top and on the bottom of the support in order to move and hold onto the rails. Also, there are two ball bearings on the sides in order to eliminate the rotational movement of the bridge around itself.

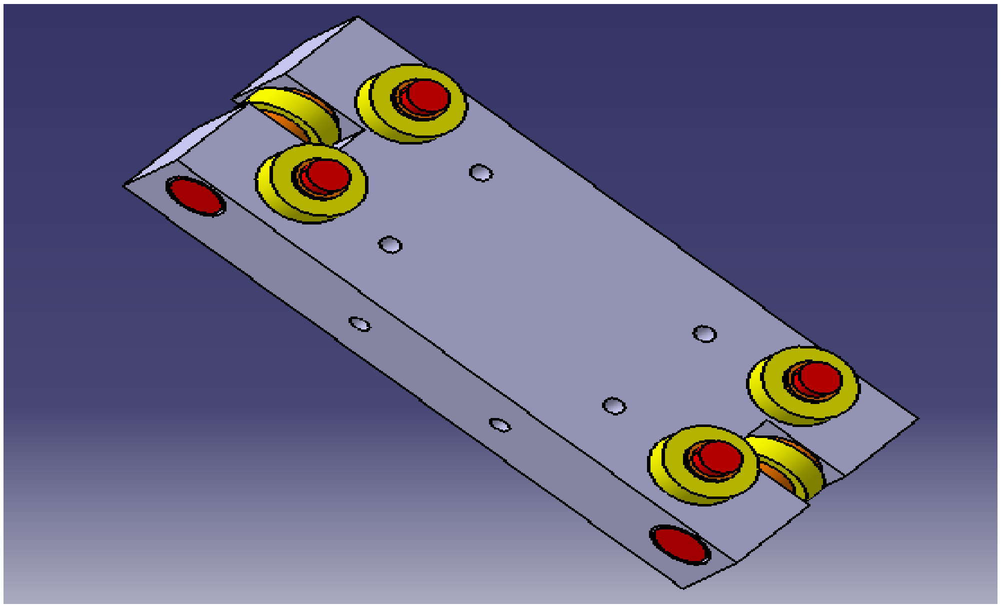


Fig. 5.3 End truck mechanism

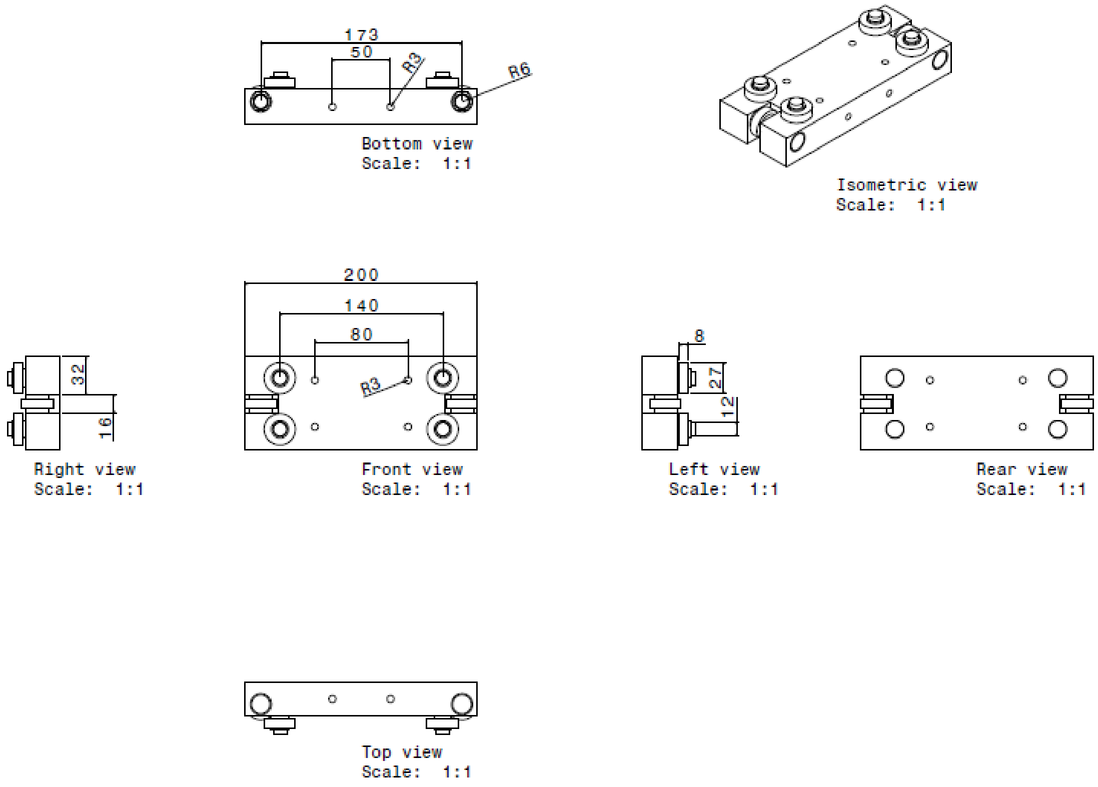


Fig. 5.4 Schematic for end truck mechanism

5.2.2 Other Alternatives:

Not only mechanical alternatives were needed, but also electronic alternatives were needed. For instance, we needed to power the LBCMM electronic systems through a variable power supply in order to power 3.3V to the PIC18F87k22 and 5V to the PIC18F4550 and the rest of the electronic gadgets. This below is a variable power supply that supplies a variable voltage between 5 and 22 volts and up to 1 ampere. In order to obtain 3.3v, we put two diodes (1N4148) in series where voltage is cut back to 3.6v and a 3.3V Zener diode does the rest of the work.

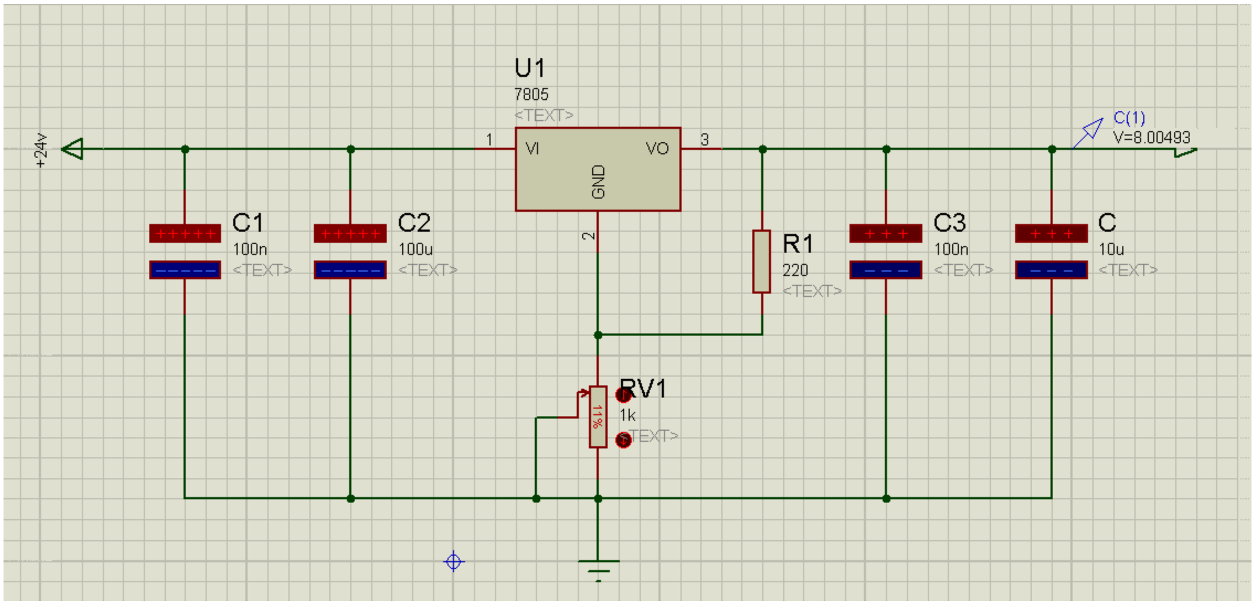


Fig. 5.5 Power supply circuit

Another problem that we faced throughout this project is the laser distance sensor. The actual laser distance sensor with a 200mm range and a 4µm resolution costs a price of 1140 € which is very high taking into account our capabilities. As a fit solution, we bought an optical distance sensor with a 200mm range and a 1mm resolution. This solution was poor but fit to our financial capabilities. Information about this sensor is shown below in the table.

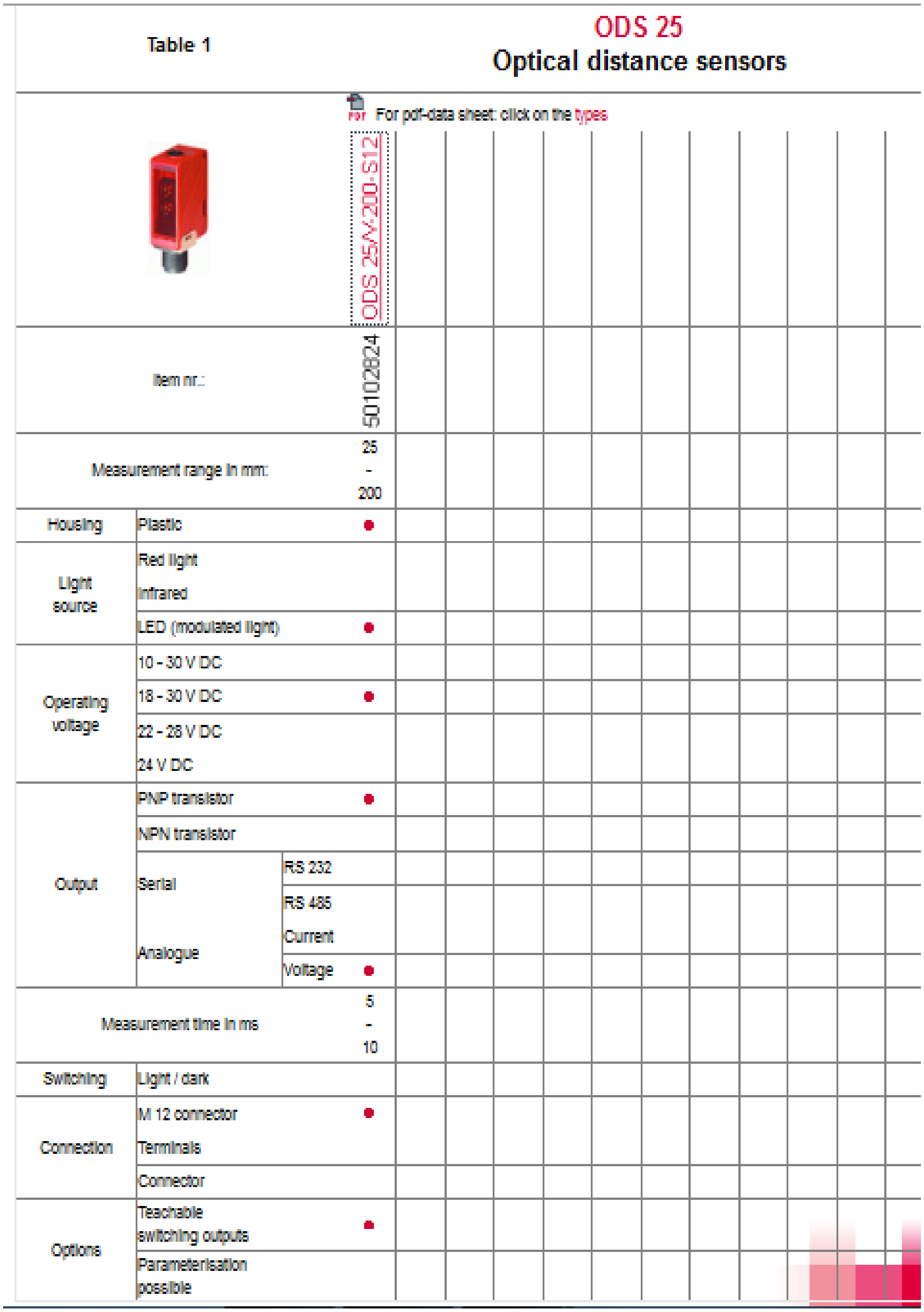


Table 1

ODS 25
Optical distance sensors

For pdf-data sheet: click on the types

			ODS 25/V-200-S12
Item nr.:			50102824
Measurement range in mm:			25 - 200
Housing	Plastic		●
Light source	Red light		
	Infrared		
	LED (modulated light)		●
Operating voltage	10 - 30 V DC		
	18 - 30 V DC		●
	22 - 28 V DC		
	24 V DC		
Output	PNP transistor		●
	NPN transistor		
	Serial	RS 232	
		RS 485	
	Analogue	Current	
		Voltage	●
Measurement time in ms			5 - 10
Switching	Light / dark		
Connection	M 12 connector		●
	Terminals		
	Connector		
Options	Teachable switching outputs		●
	Parameterisation possible		

Table 5.1 ODS Sensor features

In order to feed the sensor properly, the supply voltage must be between 18-30 volts. Also, if the optical sensor is very close and the receiver's resistance become very low (close to zero) then the short circuit current must not surpass 25mA or else the sensor can be damaged from overcurrent. So far, from the previous alternatives, we were able to provide the voltage needed. As for the current limiting, we had to make a new electronic circuit that can do the job. The current limiting circuit, as shown below, consists of a regulator, a transistor, and a potentiometer as the key elements. The main function in this circuit is done by the transistor. As the voltage on the base of the transistor changes the short circuit current changes as well. So the adjustment is made by the potentiometer where we will make the highest short circuit current 24mA according to the simulation result in the figure below.

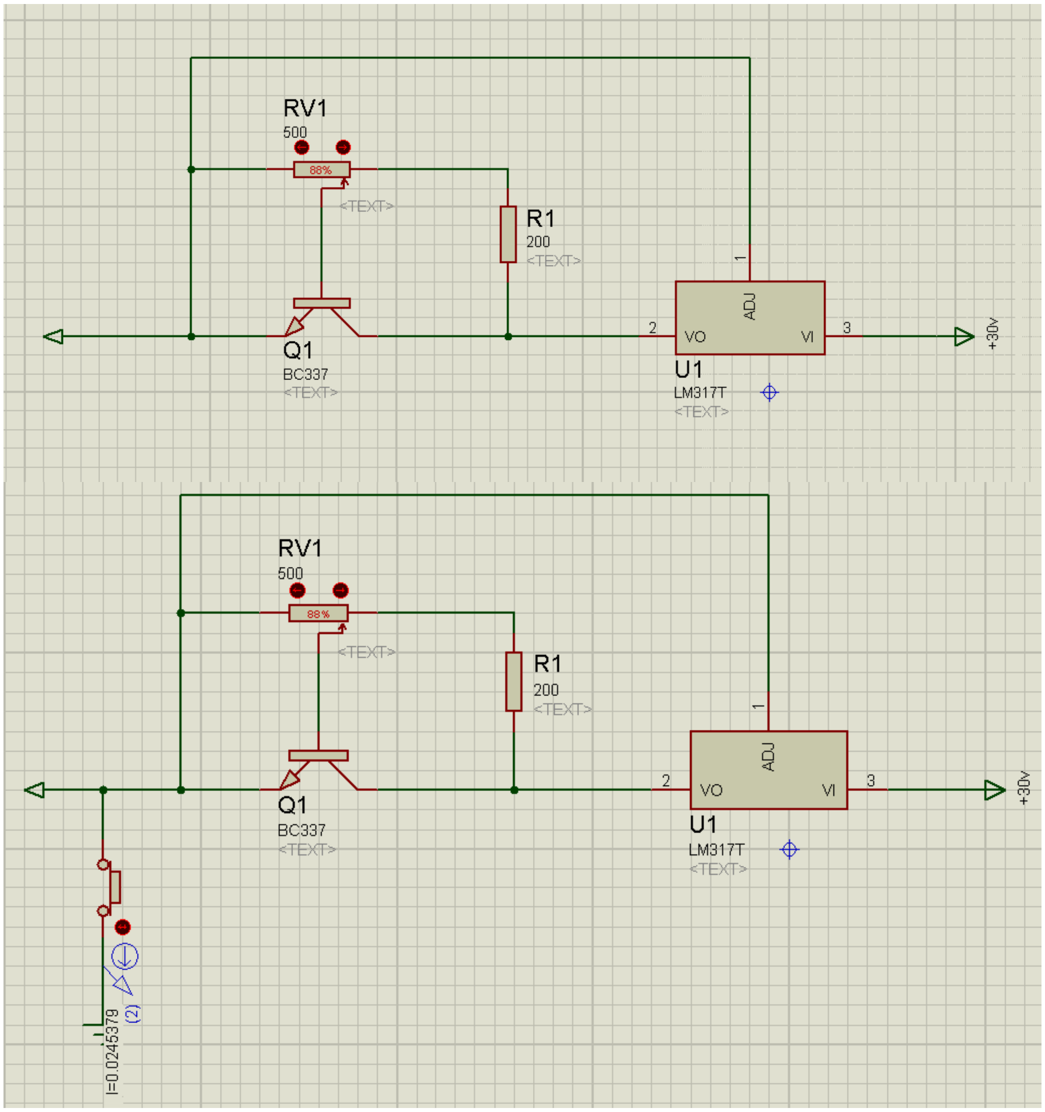


Fig. 5.6 Current limiter circuit

5.3 Results:

While working in this project and simulating it, we were able to obtain the results we looked for. These results are actually partially theoretical and partially practical. As for the practical, due to complications, we were only able to move both the x-axis and the y-axis in manual mode with no feedback results because of the problems found in the encoders. Theoretically, we were able to simulate the full control system on Proteus ISIS and obtain what we wanted. This will be explained thoroughly below.

5.3.1 Simulation on Proteus ISIS 7.9:

As shown in the electronic schematic below, our project consisted of units for signal input, logic processing, signal output, signal amplification, and system actuating. As for the input signal, it either comes from the manual mode push button signals or/and by the automatic mode signals received through serial RS232 communication. After that, these signals are conditioned and processed by the microcontrollers. The microcontrollers then send signals to the electrical amplification unit and start to read incoming signals from the feedback units (encoders, optical distance sensor, and the potentiometer). In a thoroughly manner, the microcontroller will keep processing the data and will send the x-axis, y-axis, and z-axis positions of the point read by the sensors through the serial communication to the computer. This is shown in the schematic where the serial communication port is attached to both the transmit and receive of the microcontrollers. When signals reach the electrical amplification unit, we are also able to see the electromechanical unit (motor) rotate and the encoder pulses start to input as feedback. While simulating this schematic, the only problem that faced us is the overload on the computer due to its large size and its many functions. To solve this problem, we split the units separately and tested each unit precisely. They gave perfect results and worked as expected. The units are shown below in detail.

Schematic is called full pro in adobe reader in the folder. It is A2

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Appendix I

DC brushed servo motor and drive

Appendix I: DC brushed servo motor and drive

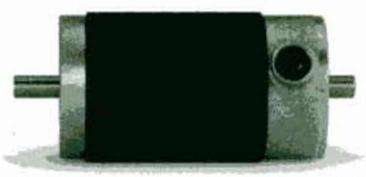
The 0642-01-010 motor series was used in due of its availability and features. The shape of the motor is shown in the next figure and the data sheet of it in the next page.

Fig.I: DC brushed servo motor

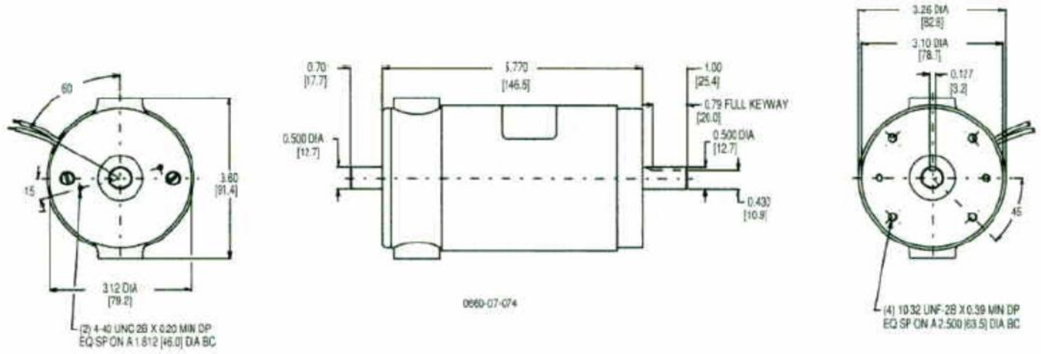
DC Motor Only

MOTOR RATINGS (up to 155°C Armature Temp.)	0642-01-010 NEMA 42C	0643-03-003 NEMA 42C	0644-06-011 NEMA 42C	0660-07-074	0723-01-045
Continuous Stall Torque (oz-in)	94	155	192	122	400
Peak Torque (before demagnetization) (oz-in)	480	720	960	680	2000
Maximum Terminal Voltage (V)	60	60	60	60	107
Maximum Opertaing Speed (rpm)	4800	4800	1850	4600	3030
MECHANICAL DATA					
Armature Moment of Inertia (oz-in-sec^2)	.0192	.0304	.0368	.0320	.2000
Mechanical Time Constant (msec)	9.4	7.1	4.7	13.1	12.78
Damping Constant (oz-in/krpm)	1.5	2.56	2.56	7.0	10
Thermal Resistance (°C/watt)	2.7	2.2	1.9	2.8	1.3
Maximum Armature Temperature (°C)	155	155	155	155	155
Maximum Friction Torque (lb-in)	0.5	0.5	0.5	0.4	0.938
Maximum Shaft Radial Load (lbs) (1" from front bearing continuous)	30	30	30	30	40
Weight (lbs)	7.5	10	11.5	6.0	12.5
WINDING DATA					
K_T Torque Constant ± 10% (oz-in/amp)	11.84	16.8	43.8	15.7	48.2
K_E Voltage Constant ± 10% (V/krpm)	8.7	12.4	32.4	11.6	35.5
Winding Resistance ± 15% @ 25°C (Ω)	0.34	0.32	1.5	0.7	.95
Electrical Time Constant (msec)	1.0	1.1	1.9	3.0	5.79
Maximum Pulse Current (A)	40	43	22	48	46
Armature Inductance (mH)	0.5	0.7	3.3	2.1	6.1

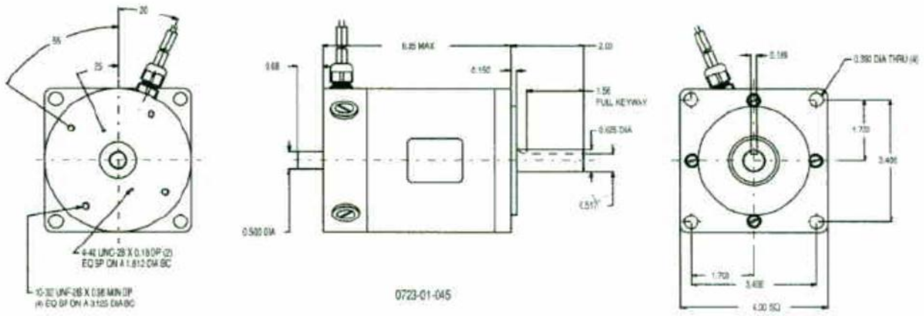
*(1/2" from front bearing continuous)


Typical 0660


Typical 0723



0660-07-074

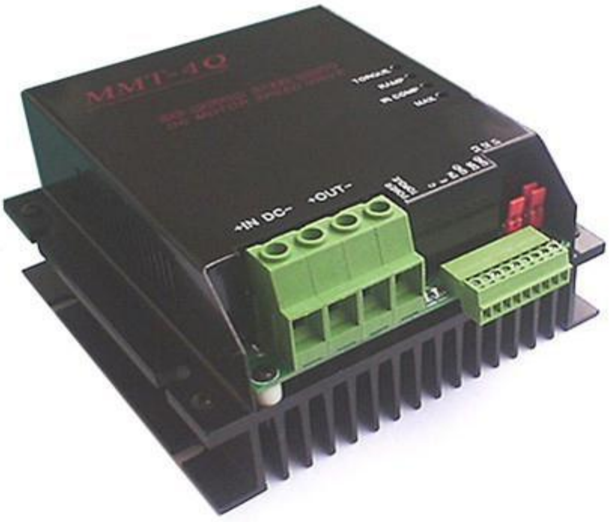


0723-01-045

For Optical Encoder Options, see Page 193
LEAD WIRE COLOR CODE: Red = Motor + CW, Black = Motor

MMT-4Q

DC24/50BL-4Q02
DC36/50BL-4Q02
DC48/50BL-4Q02
Product Operation Instruction



Fuzhou Landtop Co., Ltd

Address: No.02, 23 Flr. Longsheng Bldg.-South, Dongjie Road, Fuzhou, Fujian, China.
Postal code: 350000
Tel: 0086- 591-87553022
Fax: 0086-591-87553122
Website: www.land-top.com
Email: sales3@land-top.com

Please read the operation instruction carefully prior to using this product.

Any fault and loss due to not complying with the cautions of operation and installation instructions is not within the scope of the warranty, and manufacturer will not undertake the related responsibility for that. Please keep all documents handy, and for any enquiry, please contact the manufacturer.

Safe Cautions

·Please arrange professional technicians for installation, connection and debugging of the equipment.

·In the charged case, it is forbidden to install, remove or change the circuit of equipment.

·Please equip with necessary protector between the power input terminal and the power supply (storage battery) for this product to avoid dangerous accidents or critical damages; over current protector, fuse, emergency switch, etc. shall be installed.

·Please keep isolation and insulation protection for the product, earth, and all equipments.

·If should it be deemed necessary to debugging the equipment in a charged case, please select non-metal special screwdriver or special debugging tool.

·The produce shall be installed under a good ventilation circumstance.

·This product can not be used under abnormal environment full of high humid, dust, corrosion gas and strong vibration.

⚠ This sign means an important prompt or warning.

Catalogue

Specification and model:

Model	Maximum Output current DC: (A)	Maximum Output voltage DC: (V)	Direct voltage Working range DC: (V)
DC24/50BL-4Q02	50	24	20-28
DC36/50BL-4Q02	50	36	32-40
DC48/50BL-4Q02	50	48	44-55

Ⅰ. Product features:

This series of speed regulator is DC 4-quadrant pulse width modulation with low voltage that adopts special PIC chip to get intelligent control with features of fast responding speed, stable operation, reliable workings, complete protection functions, etc.

◆ Pulse width modulation

Low-noise, high-efficiency and low-maintenance can greatly improve the service life of DC motor.

◆ 4-quadrant operating mode

◆ Enable/reversing terminals

Realizing one of relevant functions is available through simple switch quantity without source and open circuit of transistor collector.

◆ Status indicator lamp.

Provide visualization for speed regulator in respect of power indication and overcurrent alarm.

◆ setting function for output current (amplitude limiting) ◆ Torque compensation function

◆ Dual closed loops PI adjustment (current and voltage) ◆ Standard analog quantity signal control.

Analog quantity: controls of 0-5V 0-10V, potentiometer and PWM are all Available.

◆ Voltage input with wide range: 20-55V. ◆ Overcurrent protection

◆ Overheating protection

In case of over-temperature, speed regulator will stop output to protect the safety of motor and speed controller.

II. Specification and indexes

1. PWM pulse width modulation
2. Speed regulation ratio: 1:80
3. Input selection of potentiometer and analog /PWM signal:

PWM control: frequency is 500HZ, amplitude is 5V, and duty cycle is 0-100%, Potentiometer control: 10K /3W.

4. Input voltage: 20-55 VDC.
5. Output current: 0-50A (amplitude limiting).
6. Input impedance: ≥50KΩ.
7. Rotating speed (benchmark precision %): 1 %.
8. Soft starting time: 0.3-20 S.
9. Ambient temperature: -10℃~+60℃.
10. Ambient humidity: ≤80%RH (non condensing)
11. Dielectric voltage withstand: 1100V DC 1 minute
12. Dielectric resistance: ＞ 20 MΩ
13. Leakage current: ≤ 0.9 mA
14. Weight: 0.9Kg
15. Suitable for rare earth, permanent magnet, and separate excitation• motors

III. Overall dimension: see Figure 1-1

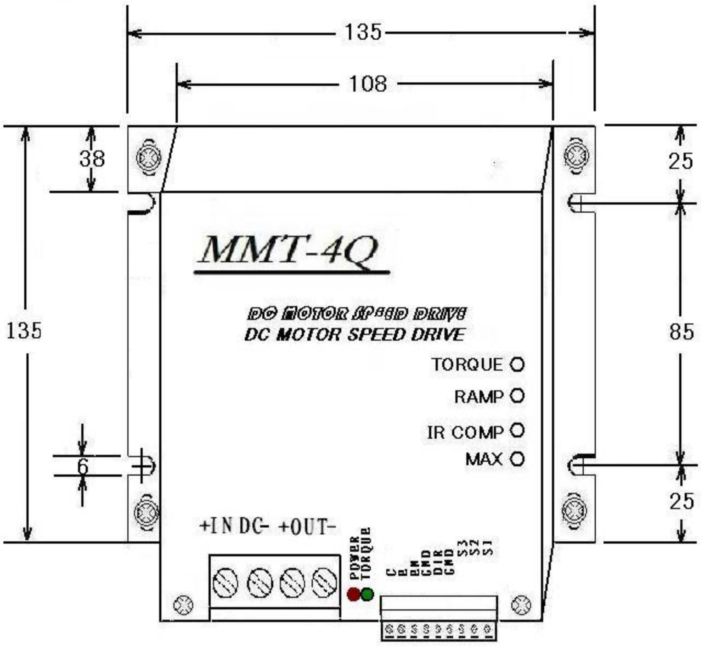


Figure 1-1

Overall dimension of radiator sees Figure 1-2

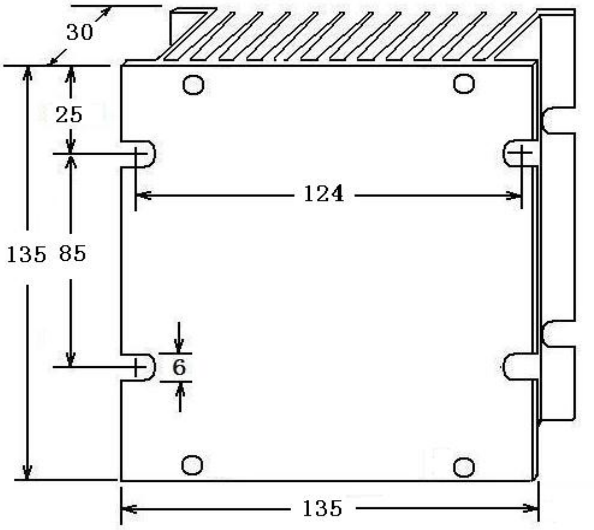


Figure 1-2

IV. Installation requirements:

⚠ Warning

1. It is forbidden to install, wire or remove controller in a charged case, otherwise, it may cause accident or grievous injury. Prior to the installation, please carefully read and acknowledge the "Safety warning content" (page 1) and strictly comply with the regulated requirements.
2. Drive elements are very sensitive to the disturbance of electromagnetic field; therefore, avoid installation under the circumstance with potential incident of static. Otherwise, it will cause damage to speed controller.
3. Keep the driver far away from dust and high humidity environment, in the meantime, avoid accidental contact. Leave enough space for driver to be easy for ventilation and adjustment.
4. Keep the driver far away from other heat sources when fixing controller to ensure controller work within specified ambient temperature range.
5. Avoid installation on the equipment with much vibration; if necessary, please take good quake-proof measures.

V. Wiring requirements:

1. Do not connect wires in a charged case.

2. Please select compatible insulated conductor and shielding line with the voltage and current of driver for connection, and specification of driver power input line and motor connecting line complies with Table 1 as follows:

Line specification and length table

Current (A)	Line specification (m ㎡)	Maximum line length(m)
50	**10**	**15**

3. Select shielding line for connecting signal wire and control line, and separately arrange to wire for power inlet line and output line.

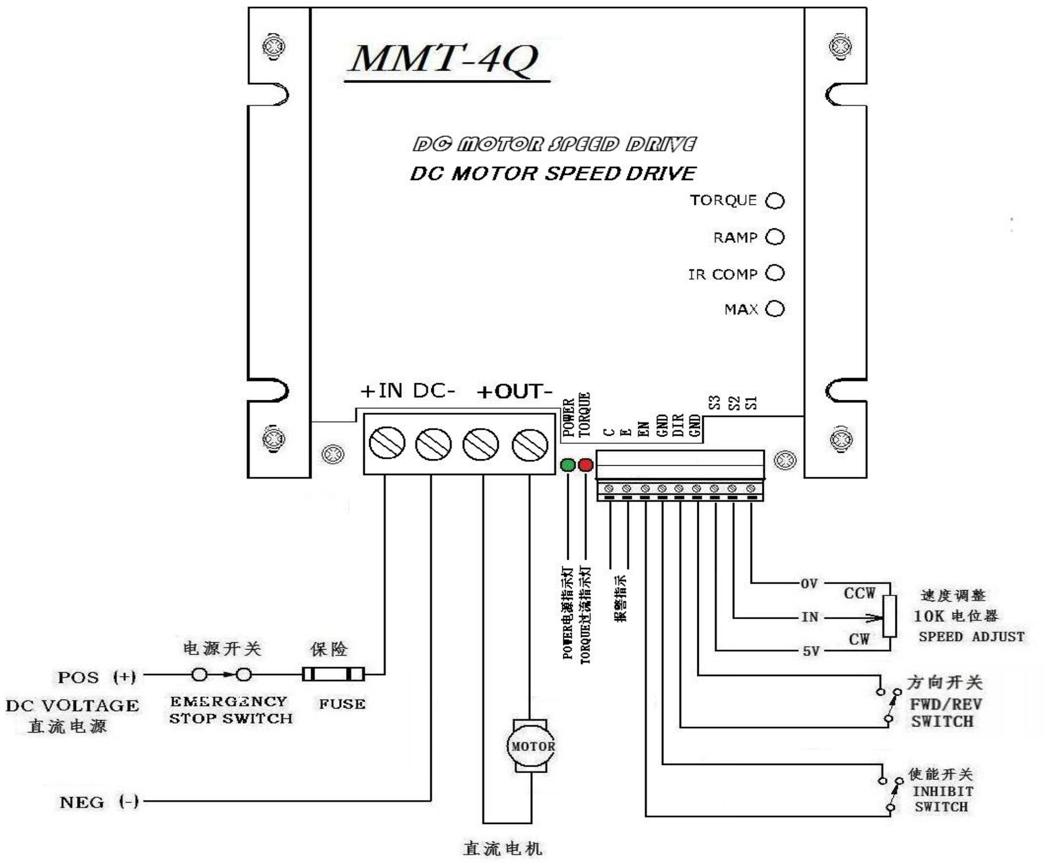
⚠ Warning

In any case, signal wire and logic control line are forbidden to bind and mix with power inlet line, output line (motor line) and other power line for wiring because it will generate induced voltage to cause interference, malfunction or direct damage for driver.

4. There is no reverse connection protection inside the driver, so please ensure positive and negative poles of driver power input and external power supply are consistent, otherwise it will cause damage to driver.

5. Please use suitable tools for connecting and must ensure accurate wiring.

VI. Driver wiring instruction on driver terminal and function diagram of terminal:



图片

中文	英文
电源指示灯	Power light
过流指示灯	Overcurrent indicator light
报警指示	Alarm indicator

Figure 2

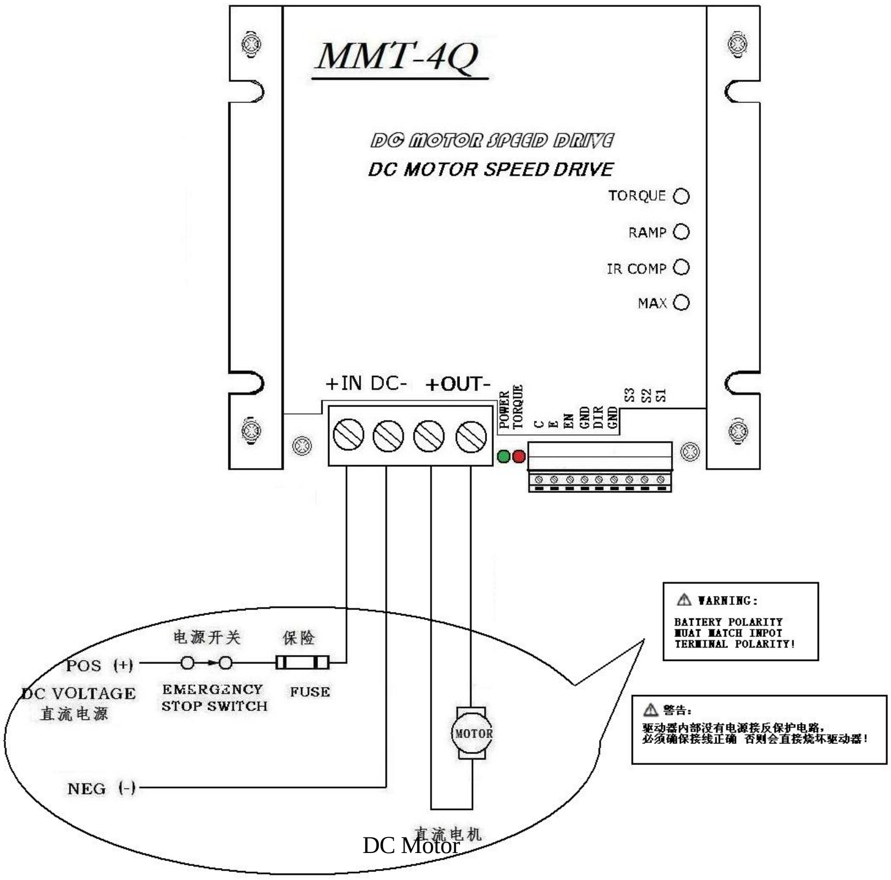
VII. Connection for fuse, power switch and motor

1. It must be equipped with a fast fuse and electromagnetic relay contactor between power input end of driver and power supply (storage battery) to realize emergency power off in case of emergency. See Figure 3

   (Note: selection for fast fuse and battery main switch: the rated current value should be bigger or equal to 150-200% of motor rated current)

   Note: please confirm that rated voltage of motor matches the output voltage of the driver.

2. Connection for motor: see Figure 3



图片	
中文	英文
警告： 驱动器内部没有电源接反保护电路，必须确保接线正确，否则会直接烧坏驱动器	Warning There is no storage battery polarity transposition inside the driver to protect circuit, and must ensure correctly connect wires, otherwise, it will directly cause burnout to the driver.

Figure 3

3. Power input connection

⚠ Warning

There is no storage battery polarity transposition for power input end inside the driver to protect circuit. Please confirm POS (+) be connected with B+ terminal and NEG (-) with B- terminal.

1. Prior to connecting power supply (storage battery) for driver, please confirm the positive and

negative poles of power supply (storage battery) in accordance with D.C positive and negative poles of driver

2. Complying with the requirements of Table 1 in page 5, select suitable wires for connection.
3. Confirm if the voltage of power supply (storage battery) can meet working requirements of driver and the capacity of power supply (storage battery) can bear load current of motor.

VII. Connection of speed adjusting potentiometer: Installation: see Figure 4

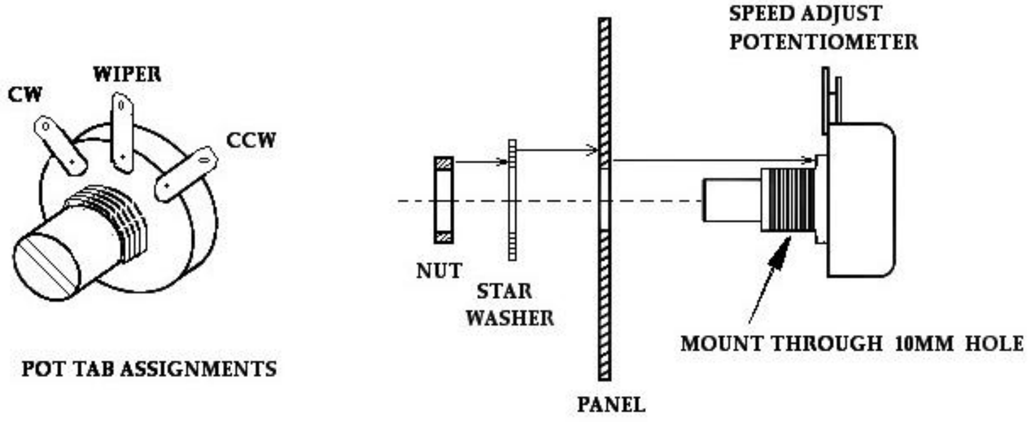


Figure 4

Warning

Please ensure the dielectric resistance between exposed lead terminal of speed regulator and installed shell ≥20MΩ.

Connections see Figure 5

According to Figure 5, use speed adjusting potentiometer, connect adjusting Potentiometer with 10K resistance among terminals, 5V, IN and 0V, and the setting of contact pin locating on the lower right corner of control refers to Figure as follows.

Warning

All connecting wires of control terminal shall not be close to the wires of power source and output terminals.

To avoid unnecessary signal interference, shorten wire length of control terminal as possible, and in case of above 0.5m, please select shielded wire.

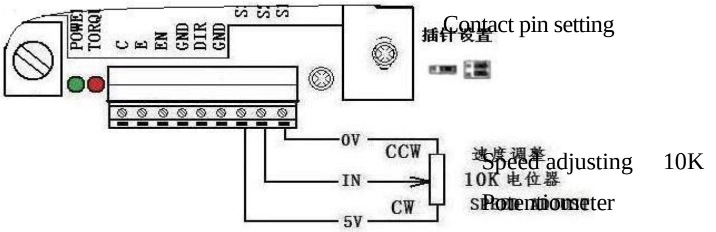


Figure 5

IX. Function and connection of control terminal: see Figure 6

Warning

All connecting wires of control terminal shall not be close to the wires of power source and output terminals.

To avoid unnecessary signal interference, shorten wire length of control terminal as possible, and in case of above 0.5m, please select shielded wire.

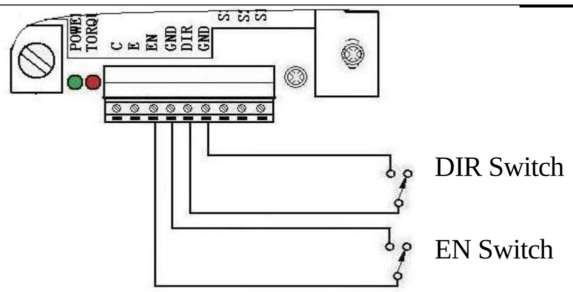


Figure 6

1. EN Enable control

Enable control: Control start-stop for motor.

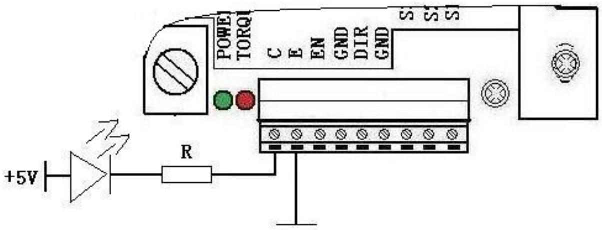
On for enable switch, driver will automatically lock interior circuit to stop output;
Off for enable switch, motor will run at the setting value of potentiometer or input signal;

2. DIR: direction control terminal

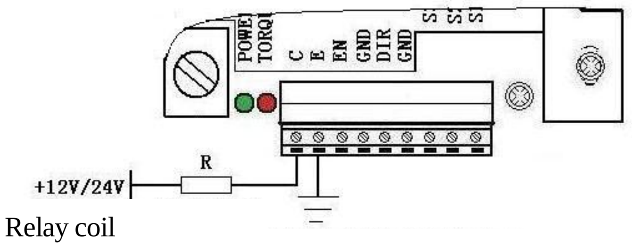
Motor rotation direction control: control moto rotation direction through on/off of direction

3. C E (OC door alarm output)

Interior design of "OC door alarm output" is that send overcurrent signal through one optocoupler to reach alarm purpose. In case of control testing overcurrent, overcurrent signal will be sent to diode ports of optocoupler to make break-over for optocoupler and overcurrent signal will be sent to C and E ports. Clients can connect wires according own requirements. Figure 7-1 is for leading overcurrent indicator light out, and figure 7-2 is for sucking of relay after overcurrent to reach alarm purpose.



Wiring instruction on alarm indicator light Figure 7-1



Alarm relay inputting wirings Figure 7-2

X. Control methods and connection of external analog quantity: see Figure 8

⚠ Warning

All connecting wires of control terminal shall not be close to the wires of power source and output terminals.

To avoid unnecessary signal interference, shorten wire length of control terminal as possible, and in case of above 0.5m, please select shielded wire.

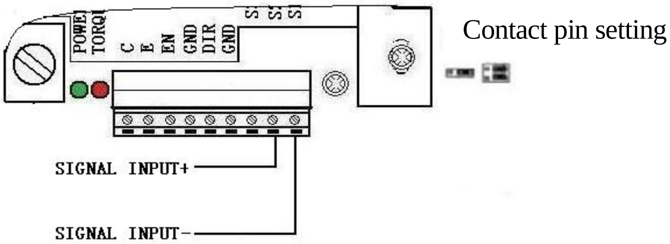


Figure 8

XI. Control mode and connection of external PWM signal: see Figure 9

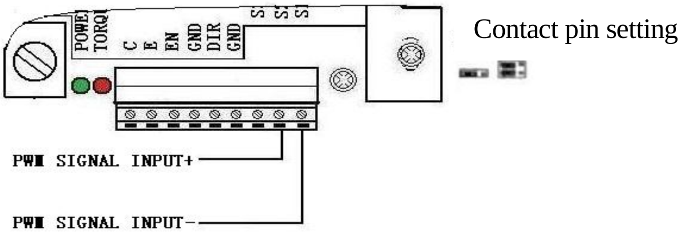


Figure 9

XII. Instruction on LED status lamp:

1. POWER (green): Power indicator light.

After being on power, this indicator light working shows that control is normal.

2. TORQUE (red): Overcurrent indicator light.

In case of TORQUE light lighting, it means that the output current of this control have already exceeded the current preset by users.

XIII. Functions instruction for adjustable potentiometer:

1. MAX (Maximum rotating speed limit)

   It is for limiting maximum rotating speed of motor that speed increases in case of clockwise adjustment for potentiometer, while decreases in case of anticlockwise.

2. IR COMP (Moment compensation)

   Adjust this potentiometer of "**IR COMP**" to make motor run under different load with constant rotating speed (Generally, factory default of this function is 0 compensation) that anticlockwise adjustment is for decreasing moment compensation, while clockwise is for increasing.

3. RAMP (soft start-stop)

   Adjust potentiometer of "RAMP" to set start-stop time (0.3-20s) for motor that clockwise adjustment is for increasing, while anticlockwise is for decreasing.

4. TORQUE (current limiting adjustment)

   Adjust this potentiometer" of TORQUE" to set overcurrent protection value for controller with adjustment range of 0-50A that adjustment is for increasing, while anticlockwise is for decreasing. After reaching current limiting value, overcurrent indicator light (red light) will light, and current will be limited on this value that at this moment, continue to adjust external signal potentiometer will not change current value (that is amplitude limiting).

XIV. Checking steps prior to power for driver:

1. At first, check if the connection of positive and negative poles of battery and driver is correct and reliable, and if the power supply belongs to the application range of driver.
2. Check if the bare parts of driver circuit plate are clean without existence of conductive metal, moist, water and sundries.
3. Check if peripheral connecting wires of driver is correct, and ensure there is no short circuit and be earthed.

   (Correct methods of connecting see Figure 2)
4. Confirm external speed adjusting potentiometer on the minimum position (given signal is under 0 state).

XV. Common fault analysis and solution:

Fault	**Possible Cause**	**Solution**
Power light is off after power on	Without power input	Measure if the voltage of power input ends is equal to power supply voltage or not. And check switches and connecting wires if failing to meet.
Without output	1、Enable 2、Error for input signal 3、Overtemperature protection	1、Measure if the voltage between EN and GND is 0V. If not, check EN switch and relevant wirings. 2、Check if signal input is normal and position of contact pin is correct. 3、Power up after the temperature of controller falling
Moment of force can not reach required value	IR COMP potentiometer	Appropriately clockwise adjust IR COMP potentiometer to reach requirements.
Abnormal positive and reverse rotation.	No reversing	Check DIR change-over switch that if close DIR switch, the voltage of DIR to ground should be 0V, while if switch off DIR switch, the voltage should be 13.7V. Check DIR switches and connecting wires if failing to meet.
Given signal is abnormal	No given signal	Terminal 9-foot should increase along with clockwise adjustment. If not, check if there is 14V of voltage for terminal 8-foot and if the position of switch contact pin is corresponding
Output voltage is not enough	1、Signal is not enough 2、Output power voltage or power current is not enough	1、Adjust signal to required value 2、Equip with power supply with sufficient capacity. 3、Adjust MAX potentiometer to required output voltage value.
Can not reach output current	1、Current potentiometer is not suitable. 2、Capacity of power supply is too small.	1. Adjust TORQUE potentiometer 2. Increase power supply capacity

Appendix II

PIC18F87k22
Microcontroller Datasheet

PIC18F87K22 Family Data Sheet

64/80-Pin, High-Performance,
1-Mbit Enhanced Flash Microcontrollers
with 12-Bit A/D and
nanoWatt XLP Technology

Note the following details of the code protection feature on Microchip devices:

- Microchip products meet the specification contained in their particular Microchip Data Sheet.
- Microchip believes that its family of products is one of the most secure families of its kind on the market today, when used in the intended manner and under normal conditions.
- There are dishonest and possibly illegal methods used to breach the code protection feature. All of these methods, to our knowledge, require using the Microchip products in a manner outside the operating specifications contained in Microchip's Data Sheets. Most likely, the person doing so is engaged in theft of intellectual property.
- Microchip is willing to work with the customer who is concerned about the integrity of their code.
- Neither Microchip nor any other semiconductor manufacturer can guarantee the security of their code. Code protection does not mean that we are guaranteeing the product as "unbreakable."

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Microchip received ISO/TS-16949:2002 certification for its worldwide headquarters, design and wafer fabrication facilities in Chandler and Tempe, Arizona; Gresham, Oregon and design centers in California and India. The Company's quality system processes and procedures are for its PIC® MCUs and dsPIC® DSCs, KEELOQ® code hopping devices, Serial EEPROMs, microperipherals, nonvolatile memory and analog products. In addition, Microchip's quality system for the design and manufacture of development systems is ISO 9001:2000 certified.

PIC18F87K22 FAMILY

64/80-Pin, High-Performance, 1-Mbit Enhanced Flash MCUs with 12-Bit A/D and nanoWatt XLP Technology

Low-Power Features:

- Power-Managed modes:
  - Run: CPU on, peripherals on
  - Idle: CPU off, peripherals on
  - Sleep: CPU off, peripherals off
- Two-Speed Oscillator Start-up
- Fail-Safe Clock Monitor
- Power-Saving Peripheral Module Disable (PMD)
- Ultra Low-Power Wake-up
- Fast Wake-up, 2 μs Typical
- Low-Power WDT, 300 nA Typical
- Ultra Low 50 nA Input Leakage
- Run mode Currents Down to Very Low 5.5 mA, Typical
- Idle mode Currents Down to Very Low 2.2 mA, Typical
- Sleep mode Currents Down to Very Low 20 nA, Typical
- RTCC Current Downs to Very Low 700 nA, Typical

Special Microcontroller Features:

- Operating Voltage Range: 1.8V to 5.5V
- On-Chip 3.3V Regulator
- Operating Speed up to 64 MHz
- Up to 128 Kbytes On-Chip Flash Program Memory
- Data EEPROM of 1,024 Bytes
- 4K x 8 General Purpose Registers (SRAM)
- 10,000 Erase/Write Cycle Flash Program Memory, Typical
- 1,000,000 Erase/write Cycle Data EEPROM Memory, Typical
- Flash Retention 40 Years, Minimum
- Three Internal Oscillators: LF-INTRC (31 kHz), MF-INTOSC (500 kHz) and HF-INTOSC (16 MHz)
- Self-Programmable under Software Control
- Priority Levels for Interrupts
- 8 x 8 Single-Cycle Hardware Multiplier
- Extended Watchdog Timer (WDT):
  - Programmable period from 4 ms to 4,194s (about 70 minutes)
- In-Circuit Serial Programming™ (ICSP™) via Two Pins
- In-Circuit Debug via Two Pins
- Programmable:
  - BOR
  - LVD

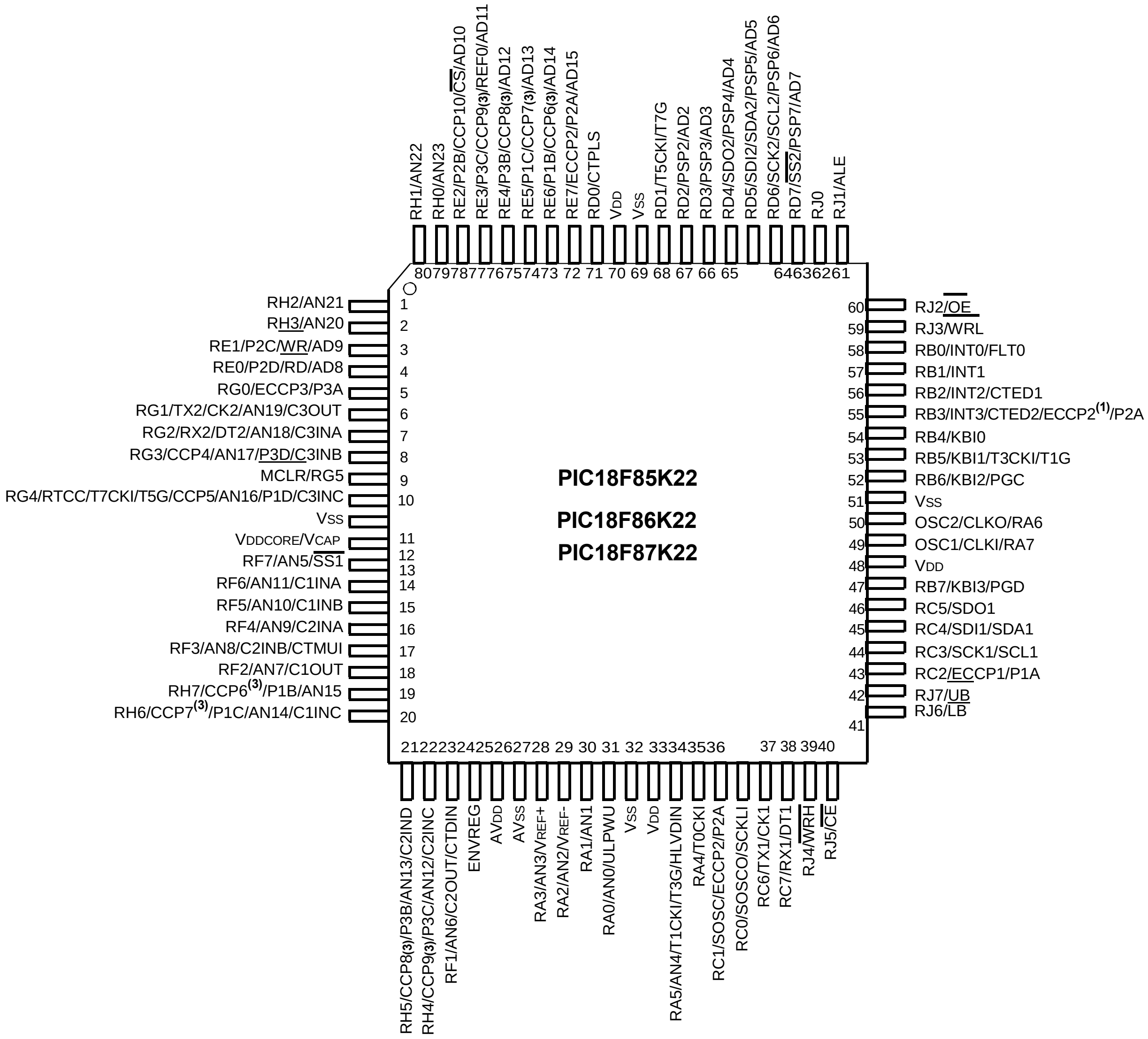
Device	Program Memory		Data Memory		I/O	12-Bit A/D (ch)	CCP/ ECCP (PWM)	MSSP			EUSART	Comparators	Timers 8/16-Bit	External Bus	CTMU	RTCC
	Flash (bytes)	# Single-Word Instructions	SRAM (bytes)	EEPROM (bytes)					SPI	Master I²C™						
PIC18F65K22	32K	16,383	2K	1K	53	16	5/3	2	Y	Y	2	3	4/4	N	Y	Y
PIC18F66K22	64K	32,768	4K	1K	53	16	7/3	2	Y	Y	2	3	6/5	N	Y	Y
PIC18F67K22	128K	65,536	4K	1K	53	16	7/3	2	Y	Y	2	3	6/5	N	Y	Y
PIC18F85K22	32K	16,383	2K	1K	69	24	5/3	2	Y	Y	2	3	4/4	Y	Y	Y
PIC18F86K22	64K	32,768	4K	1K	69	24	7/3	2	Y	Y	2	3	6/5	Y	Y	Y
PIC18F87K22	128K	65,536	4K	1K	69	24	7/3	2	Y	Y	2	3	6/5	Y	Y	Y

Peripheral Highlights:

- Up to Ten CCP/ECCP modules:
  - Up to seven Capture/Compare/PWM (CCP) modules
  - Three Enhanced Capture/Compare/PWM (ECCP) modules
- Up to Eleven 8/16-Bit Timer/Counter modules:
  - Timer0 - 8/16-bit timer/counter with 8-bit programmable prescaler
  - Timer1,3 - 16-bit timer/counter
  - Timer2,4,6,8 - 8-bit timer/counter
  - Timer5,7 - 16-bit timer/counter for 64k and 128k parts
  - Timer10,12 - 8-bit timer/counter for 64k and 128k parts
- Three Analog Comparators
- Configurable Reference Clock Output
- Hardware Real-Time Clock and Calendar (RTCC) module with Clock, Calendar and Alarm Functions
- Charge Time Measurement Unit (CTMU):
  - Capacitance measurement for mTouch™ sensing solution
  - Time measurement with 1 ns typical resolution
  - Integrated temperature sensor
- High-Current Sink/Source 25 mA/25 mA (PORTB and PORTC)
- Up to Four External Interrupts
- Two Master Synchronous Serial Port (MSSP) modules:
  - 3/4-wire SPI (supports all four SPI modes)
  - I^2C™ Master and Slave modes
- Two Enhanced Addressable USART modules:
  - LIN/J2602 support
  - Auto-Baud Detect (ABD)
- 12-Bit A/D Converter with up to 24 Channels:
  - Auto-acquisition and Sleep operation
  - Differential input mode of operation
- Integrated Voltage Reference

Pin Diagrams - PIC18F8XK22

80-Pin TQFP



Note 1: The ECCP2 pin placement depends on the CCP2MX Configuration bit setting and whether the device is in Microcontroller or Extended Microcontroller mode.

2: Not available on the PIC18F65K22 and PIC18F85K22 devices.

3: The CC6, CCP7, CCP8 and CCP9 pin placement depends on the setting of the ECCPMX Configuration bit (CONFIG3H<1>).

1.1.6 EASY MIGRATION

All devices share the same rich set of peripherals except that the devices with 32 Kbytes of program memory (PIC18F65K22 and PIC18F85K22) have two less CCPs and three less timers. This provides a smooth migration path within the device family as applications evolve and grow.

The consistent pinout scheme, used throughout the entire family, also aids in migrating to the next larger device. This is true when moving between the 64-pin members, between the 80-pin members, or even jumping from 64-pin to 80-pin devices.

All of the devices in the family share the same rich set of peripherals, except for those with 32 Kbytes of program memory (PIC18F65K22 and PIC18F85K22). Those devices have two less CCPs and three less timers.

The PIC18F87K22 family is also largely pin compatible with other PIC18 families, such as the PIC18F8720 and PIC18F8722 and the PIC18F85J11. This allows a new dimension to the evolution of applications, allowing developers to select different price points within Microchip's PIC18 portfolio, while maintaining a similar feature set.

1.2 Other Special Features

- **Communications:** The PIC18F87K22 family incorporates a range of serial communication peripherals including two Enhanced USART, that support LIN/J2602, and two Master SSP modules capable of both SPI and I^{2}C™ (Master and Slave) modes of operation.
- **CCP Modules:** PIC18F87K22 family devices incorporate up to seven Capture/Compare/PWM (CCP) modules. Up to six different time bases can be used to perform several different operations at once.
- **ECCP Modules:** The PIC18F87K22 family has three Enhanced CCP (ECCP) modules to maximize flexibility in control applications:
  - Up to eight different time bases for performing several different operations at once
  - Up to four PWM outputs for each module - for a total of 12 PWMs
  - Other beneficial features, such as polarity selection, programmable dead time, auto-shutdown and restart, and Half-Bridge and Full-Bridge Output modes
- **12-Bit A/D Converter:** The PIC18F87K22 family has differential ADC. It incorporates programmable acquisition time, allowing for a channel to be selected and a conversion to be initiated without waiting for a sampling period, and thus, reducing code overhead.
- **Charge Time Measurement Unit (CTMU):** The CTMU is a flexible analog module that provides accurate differential time measurement between pulse sources, as well as asynchronous pulse generation.
- Together with other on-chip analog modules, the CTMU can precisely measure time, measure capacitance or relative changes in capacitance, or generate output pulses that are independent of the system clock.
- **LP Watchdog Timer (WDT):** This enhanced version incorporates a 22-bit prescaler, allowing an extended time-out range that is stable across operating voltage and temperature. See **Section 31.0** "**Electrical Characteristics**" for time-out periods.
- **Real-Time Clock and Calendar Module (RTCC):** The RTCC module is intended for applications requiring that accurate time be maintained for extended periods of time with minimum to no intervention from the CPU.
- The module is a 100-year clock and calendar with automatic leap year detection. The range of the clock is from 00:00:00 (midnight) on January 1, 2000 to 23:59:59 on December 31, 2099.

1.3 Details on Individual Family Members

Devices in the PIC18F87K22 family are available in 64-pin and 80-pin packages. Block diagrams for the two groups are shown in Figure 1-1 and Figure 1-2. The devices are differentiated from each other in these ways:

- Flash Program Memory:
  - PIC18FX5K22 (PIC18F65K22 and PIC18F85K22) - 32 Kbytes
  - PIC18FX6K22 (PIC18F66K22 and PIC18F86K22) - 64 Kbytes
  - PIC18FX7K22 (PIC18F67K22 and PIC18F87K22) - 128 Kbytes
- Data RAM:
  - All devices except PIC18FX5K22 - 4 Kbytes
  - PIC18FX5K22 - 2 Kbytes
- I/O Ports:
  - PIC18F6XK22 (64-pin devices) - seven bidirectional ports
  - PIC18F8XK22 (80-pin devices) - nine bidirectional ports
- CCP modules:
  - PIC18FX5K22 (PIC18F65K22 and PIC18F85K22) - five CCP modules
  - PIC18FX6K22 and PIC18FX7K22 (PIC18F66K22, PIC18F86K22, PIC18F67K22, and PIC18F87K22) - seven CCP modules
- Timer modules:
  - PIC18FX5K22 (PIC18F65K22 and PIC18F85K22) - Four 8-bit timer/counters and four 16-bit timer/counters
  - PIC18FX6K22 and PIC18FX7K22 (PIC18F66K22, PIC18F86K22, PIC18F67K22, and PIC18F87K22) - six 8-bit timer/counters and five 16-bit timer/counters
- A/D Channels:
  - PIC18F6XK22 (64-pin devices) - 24 channels
  - PIC18F8XK22 (80-pin devices) - 16 channels

All other features for devices in this family are identical. These are summarized in Table 1-1 and Table 1-2.

The pinouts for all devices are listed in Table 1-3 and Table 1-4.

11.0 INTERRUPTS

Members of the PIC18F87K22 family of devices have multiple interrupt sources and an interrupt priority feature that allows most interrupt sources to be assigned a high-priority level or a low-priority level. The high-priority interrupt vector is at 0008h and the low-priority interrupt vector is at 0018h. High-priority interrupt events will interrupt any low-priority interrupts that may be in progress.

The registers for controlling interrupt operation are:

- RCON
- INTCON
- INTCON2
- INTCON3
- PIR1, PIR2, PIR3
- PIE1, PIE2, PIE3
- IPR1, IPR2, IPR3

It is recommended that the Microchip header files supplied with MPLAB® IDE be used for the symbolic bit names in these registers. This allows the assembler/compiler to automatically take care of the placement of these bits within the specified register. In general, interrupt sources have three bits to control their operation. They are:

- **Flag bit** - Indicating that an interrupt event occurred
- **Enable bit** - Enabling program execution to branch to the interrupt vector address when the flag bit is set
- **Priority bit** - Specifying high priority or low priority

The interrupt priority feature is enabled by setting the IPEN bit (RCON<7>). When interrupt priority is enabled, there are two bits that enable interrupts globally. Setting the GIEH bit (INTCON<7>) enables all interrupts that have the priority bit set (high priority). Setting the GIEL bit (INTCON<6>) enables all interrupts that have the priority bit cleared (low priority). When the interrupt flag, enable bit and appropriate global interrupt enable bit are set, the interrupt will vector immediately to address, 0008h or 0018h, depending on the priority bit setting. Individual interrupts can be disabled through their corresponding enable bits.

When the IPEN bit is cleared (default state), the interrupt priority feature is disabled and interrupts are compatible with PIC® mid-range devices. In Compatibility mode, the interrupt priority bits for each source have no effect. INTCON<6> is the PEIE bit that enables/disables all peripheral interrupt sources. INTCON<7> is the GIE bit that enables/disables all interrupt sources. All interrupts branch to address 0008h in Compatibility mode.

When an interrupt is responded to, the global interrupt enable bit is cleared to disable further interrupts. If the IPEN bit is cleared, this is the GIE bit. If interrupt priority levels are used, this will be either the GIEH or GIEL bit. High-priority interrupt sources can interrupt a low-priority interrupt. Low-priority interrupts are not processed while high-priority interrupts are in progress. The return address is pushed onto the stack and the PC is loaded with the interrupt vector address (0008h or 0018h). Once in the Interrupt Service Routine, the source(s) of the interrupt can be determined by polling the interrupt flag bits. The interrupt flag bits must be cleared in software before re-enabling interrupts to avoid recursive interrupts.

The “return from interrupt” instruction, `RETFIE`, exits the interrupt routine and sets the GIE bit (GIEH or GIEL if priority levels are used) that re-enables interrupts. For external interrupt events, such as the INTx pins or the PORTB input change interrupt, the interrupt latency will be three to four instruction cycles. The exact latency is the same for one or two-cycle instructions. Individual interrupt flag bits are set regardless of the status of their corresponding enable bit or the GIE bit.

Note: Do not use the `MOVFF` instruction to modify any of the Interrupt Control registers while **any** interrupt is enabled. Doing so may cause erratic microcontroller behavior.

12.0 I/O PORTS

Depending on the device selected and features enabled, there are up to nine ports available. Some pins of the I/O ports are multiplexed with an alternate function from the peripheral features on the device. In general, when a peripheral is enabled, that pin may not be used as a general purpose I/O pin.

Each port has three memory mapped registers for its operation:

- TRIS register (Data Direction register)
- PORT register (reads the levels on the pins of the device)
- LAT register (Output Latch register)

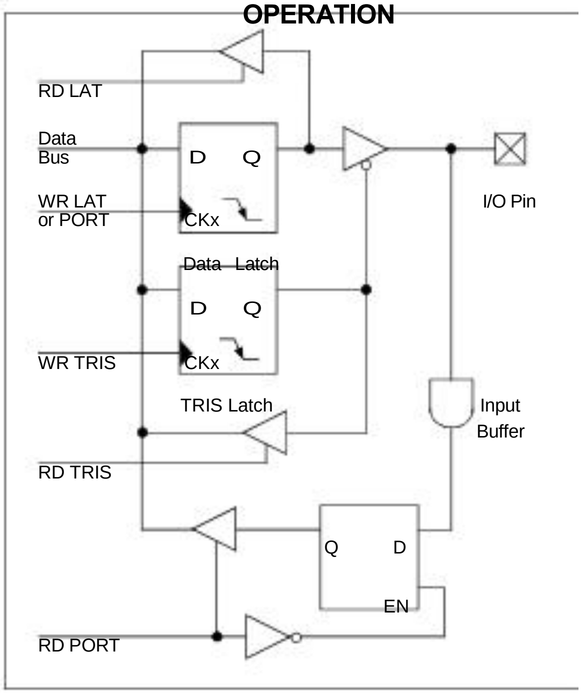
Reading the PORT register reads the current status of the pins, whereas writing to the PORT register writes to the Output Latch (LAT) register.

Setting a TRIS bit (= `1`) makes the corresponding PORT pin an input (putting the corresponding output driver in a High-Impedance mode). Clearing a TRIS bit (= `0`) makes the corresponding port pin an output (i.e., put the contents of the corresponding LAT bit on the selected pin).

The Output Latch (LAT register) is useful for read-modify-write operations on the value that the I/O pins are driving. Read-modify-write operations on the LAT register read and write the latched output value for the PORT register.

A simplified model of a generic I/O port, without the interfaces to other peripherals, is shown in Figure 12-1.

FIGURE 12-1: GENERIC I/O PORT OPERATION



12.1 I/O Port Pin Capabilities

When developing an application, the capabilities of the port pins must be considered. Outputs on some pins have higher output drive strength than others. Similarly, some pins can tolerate higher than V_{DD} input levels. All of the digital ports are 5.5V input tolerant. The analog ports have the same tolerance - having clamping diodes implemented internally.

12.1.1 PIN OUTPUT DRIVE

When used as digital I/O, the output pin drive strengths vary, according to the pins' grouping to meet the needs for a variety of applications. In general, there are two classes of output pins, in terms of drive capability:

- Outputs designed to drive higher current loads such as LEDs:
  - PORTA
  - PORTB
  - PORTC
- Outputs with lower drive levels, but capable of driving normal digital circuit loads with a high input impedance. Able to drive LEDs, but only those with smaller current requirements:
  - PORTD
  - PORTE
  - PORTF
  - PORTG
  - PORTH$^{(\dagger)}$
  - PORTJ$^{(\dagger)}$

  † These ports are not available on 64-pin devices.

12.1.2 PULL-UP CONFIGURATION

Four of the I/O ports (PORTB, PORTD, PORTE and PORTJ) implement configurable weak pull-ups on all pins. These are internal pull-ups that allow floating digital input signals to be pulled to a consistent level without the use of external resistors.

The pull-ups are enabled with a single bit for each of the ports: RBPU (INTCON2<7>) for PORTB, and RDPU, REPU and RJPU (PADCFG1<7:5>) for the other ports.

13.0 TIMER0 MODULE

The Timer0 module incorporates the following features:

- Software-selectable operation as a timer or counter in both 8-bit or 16-bit modes
- Readable and writable registers
- Dedicated 8-bit, software programmable prescaler
- Selectable clock source (internal or external)
- Edge select for external clock
- Interrupt-on-overflow

The T0CON register (Register 13-1) controls all aspects of the module's operation, including the prescale selection. It is both readable and writable.

Figure 13-1 provides a simplified block diagram of the Timer0 module in 8-bit mode. Figure 13-2 provides a simplified block diagram of the Timer0 module in 16-bit mode.

REGISTER 13-1: T0CON: TIMER0 CONTROL REGISTER

R/W-1	R/W-1	R/W-1	R/W-1	R/W-1	R/W-1	R/W-1	R/W-1
TMR0ON	T08BIT	T0CS	T0SE	PSA	T0PS2	T0PS1	T0PS0
bit 7							bit 0

Legend:

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

bit 7 **TMR0ON:** Timer0 On/Off Control bit
1 = Enables Timer0
0 = Stops Timer0

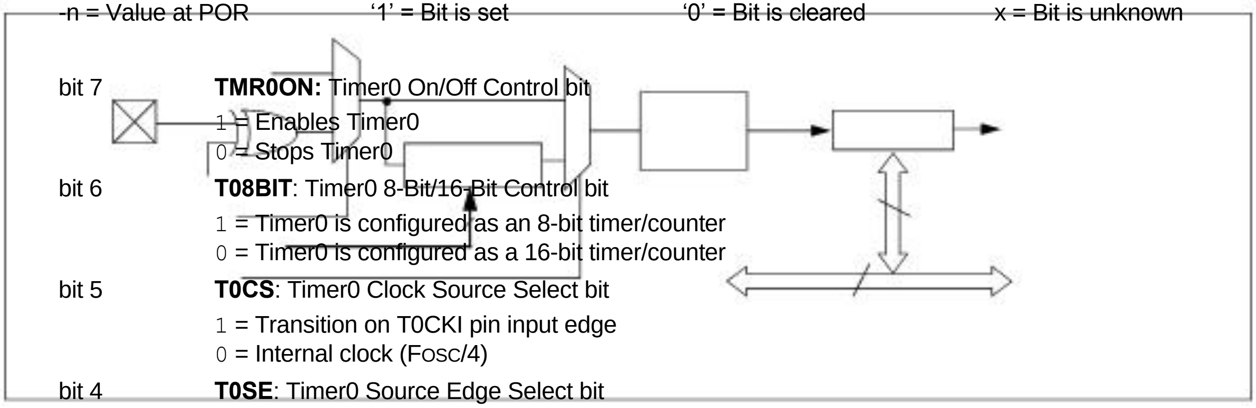
bit 6 **T08BIT**: Timer0 8-Bit/16-Bit Control bit
1 = Timer0 is configured as an 8-bit timer/counter
0 = Timer0 is configured as a 16-bit timer/counter

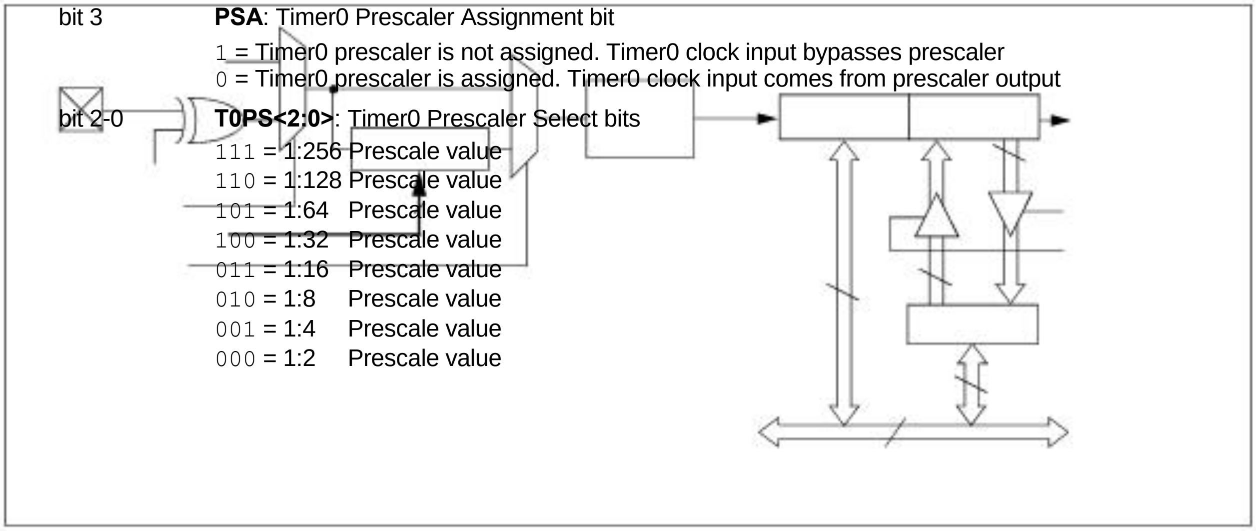
bit 5 **T0CS**: Timer0 Clock Source Select bit
1 = Transition on T0CKI pin input edge
0 = Internal clock (FOSC/4)

bit 4 **T0SE**: Timer0 Source Edge Select bit
1 = Increment on high-to-low transition on T0CKI pin
0 = Increment on low-to-high transition on T0CKI pin

bit 3 **PSA**: Timer0 Prescaler Assignment bit
1 = Timer0 prescaler is not assigned. Timer0 clock input bypasses prescaler
0 = Timer0 prescaler is assigned. Timer0 clock input comes from prescaler output

bit 2-0 **T0PS<2:0>**: Timer0 Prescaler Select bits
111 = 1:256 Prescale value
110 = 1:128 Prescale value
101 = 1:64 Prescale value
100 = 1:32 Prescale value
011 = 1:16 Prescale value
010 = 1:8 Prescale value
001 = 1:4 Prescale value
000 = 1:2 Prescale value





14.0 TIMER1 MODULE

The Timer1 timer/counter module incorporates these features:

- Software-selectable operation as a 16-bit timer or counter
- Readable and writable 8-bit registers (TMR1H and TMR1L)
- Selectable clock source (internal or external) with device clock or SOSC oscillator internal options
- Interrupt-on-overflow
- Reset on ECCP Special Event Trigger
- Timer with gated control

Figure 14-1 displays a simplified block diagram of the Timer1 module.

The Timer1 oscillator can also be used as a low-power clock source for the microcontroller in power-managed operation. The Timer1 can also work on the SOSC oscillator.

Timer1 is controlled through the T1CON Control register (Register 14-1). It also contains the Secondary Oscillator Enable bit (SOSCEN). Timer1 can be enabled or disabled by setting or clearing control bit, TMR1ON (T1CON<0>).

The FOSC clock source should not be used with the ECCP capture/compare features. If the timer will be used with the capture or compare features, always select one of the other timer clocking options.

REGISTER 14-1: T1CON: TIMER1 CONTROL REGISTER

R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
TMR1CS1	TMR1CS0	T1CKPS1	T1CKPS0	SOSCEN	$\overline{\text{T1SYNC}}$	RD16	TMR1ON
bit 7							bit 0

Legend:

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

bit 7-6	**TMR1CS<1:0>:** Timer1 Clock Source Select bits `10` = Timer1 clock source is either from a pin or oscillator,depending on the SOSCEN bit: SOSCEN = `0`: External clock from the T1CKI pin (on the rising edge). SOSCEN = `1`: Depending on the SOSCSEL Configuration bit the clock source is either a crystal oscillator on the SOSCI/SOSCO pins or an internal clock from the SCLKI pin. `01` = Timer1 clock source is the system clock (FOSC)(1) `00` = Timer1 clock source is the instruction clock (FOSC/4)
bit 5-4	**T1CKPS<1:0>:** Timer1 Input Clock Prescale Select bits `11` = 1:8 Prescale value `10` = 1:4 Prescale value `01` = 1:2 Prescale value `00` = 1:1 Prescale value
bit 3	**SOSCEN:** SOSC Oscillator Enable bit `1` = SOSC is enabled and available for Timer1 `0` = SOSC is disabled for Timer1 The oscillator inverter and feedback resistor are turned off to eliminate power drain.
bit 2	**$\overline{\text{T1SYNC}}$:** Timer1 External Clock Input Synchronization Select bit TMR1CS<1:0> = `10`: `1` = Do not synchronize external clock input `0` = Synchronize external clock input TMR1CS<1:0> = `0x`: This bit is ignored. Timer1 uses the internal clock when TMR1CS<1:0> = `1x`.
bit 1	**RD16:** 16-Bit Read/Write Mode Enable bit `1` = Enables register read/write of Timer1 in one 16-bit operation `0` = Enables register read/write of Timer1 in two 8-bit operations
bit 0	**TMR1ON:** Timer1 On bit `1` = Enables Timer1 `0`= StopsTimer1

Note 1: The FOSC clock source should not be selected if the timer will be used with the ECCP capture/compare features.

14.1 Timer1 Gate Control Register

The Timer1 Gate Control register (T1GCON), displayed in Register 14-2, is used to control the Timer1 gate.

REGISTER 14-2: T1GCON: TIMER1 GATE CONTROL REGISTER(1)

R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R-x	R/W-0	R/W-0
TMR1GE	T1GPOL	T1GTM	T1GSPM	T1GGO/$\overline{\text{T1DONE}}$	T1GVAL	T1GSS1	T1GSS0
bit 7							bit 0

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

bit 7	**TMR1GE:** Timer1 Gate Enable bit If TMR1ON = `0`: This bit is ignored. If TMR1ON = `1`: `1` = Timer1 counting is controlled by the Timer1 gate function `0` = Timer1 counts regardless of Timer1 gate function
bit 6	**T1GPOL:** Timer1 Gate Polarity bit `1` = Timer1 gate is active-high (Timer1 counts when gate is high) `0` = Timer1 gate is active-low (Timer1 counts when gate is low)
bit 5	**T1GTM:** Timer1 Gate Toggle Mode bit `1` = Timer1 Gate Toggle mode is enabled `0` = Timer1 Gate Toggle mode is disabled and toggle flip-flop is cleared Timer1 gate flip-flop toggles on every rising edge.
bit 4	**T1GSPM:** Timer1 Gate Single Pulse Mode bit `1` = Timer1 Gate Single Pulse mode is enabled and is controlling Timer1 gate `0` = Timer1 Gate Single Pulse mode is disabled
bit 3	**T1GGO/$\overline{\text{T1DONE}}$:** Timer1 Gate Single Pulse Acquisition Status bit `1` = Timer1 gate single pulse acquisition is ready, waiting for an edge `0` = Timer1 gate single pulse acquisition has completed or has not been started This bit is automatically cleared when T1GSPM is cleared.
bit 2	**T1GVAL:** Timer1 Gate Current State bit Indicates the current state of the Timer1 gate that could be provided to TMR1H:TMR1L; unaffected by Timer1 Gate Enable (TMR1GE) bit.
bit 1-0	**T1GSS<1:0>:** Timer1 Gate Source Select bits `11` = Comparator 2 output `10` = Comparator 1 output `01` = TMR2 to match PR2 output `00` = Timer1 gate pin

Note 1: Programming the T1GCON prior to T1CON is recommended.

15.0 TIMER2 MODULE

The Timer2 module incorporates the following features:

- Eight-bit Timer and Period registers (TMR2 and PR2, respectively)
- Both registers readable and writable
- Software programmable prescaler (1:1, 1:4 and 1:16)
- Software programmable postscaler (1:1 through 1:16)
- Interrupt on TMR2 to PR2 match
- Optional use as the shift clock for the MSSP modules

The module is controlled through the T2CON register (Register 15-1) that enables or disables the timer, and configures the prescaler and postscaler. Timer2 can be shut off by clearing control bit, TMR2ON (T2CON<2>), to minimize power consumption.

A simplified block diagram of the module is shown in Figure 15-1.

15.1 Timer2 Operation

In normal operation, TMR2 is incremented from 00h on each clock (FOSC/4). A four-bit counter/prescaler on the clock input gives the prescale options of direct input, divide-by-4 or divide-by-16. These are selected by the prescaler control bits, T2CKPS<1:0> (T2CON<1:0>).

The value of TMR2 is compared to that of the Period register, PR2, on each clock cycle. When the two values match, the comparator generates a match signal as the timer output. This signal also resets the value of TMR2 to 00h on the next cycle and drives the output counter/postscaler. (See **Section 15.2** “**Timer2 Interrupt**”.)

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

- A write to the TMR2 register
- A write to the T2CON register
- Any device Reset - Power-on Reset (POR), MCLR Reset, Watchdog Timer Reset (WDTR) or Brown-out Reset (BOR)

TMR2 is not cleared when T2CON is written.

Note: The CCP and ECCP modules use Timers, 1 through 8, for some modes. The assignment of a particular timer to a CCP/ECCP module is determined by the Timer to CCP enable bits in the CCPTMRSx registers. For more details, see Register 20-2, Register 19-2 and Register 19-3.

REGISTER 15-1: T2CON: TIMER2 CONTROL REGISTER

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

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

bit 7 **Unimplemented:** Read as ‘`0`’

bit 6-3 **T2OUTPS<3:0>:** Timer2 Output Postscale Select bits
`0000` = 1:1 Postscale
`0001` = 1:2 Postscale
•
•
•
`1111` = 1:16 Postscale

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

bit 1-0 **T2CKPS<1:0>:** Timer2 Clock Prescale Select bits
`00` = Prescaler is 1
`01` = Prescaler is 4
`1x` = Prescaler is 16

19.0 CAPTURE/COMPARE/PWM (CCP) MODULES

PIC18F87K22 family devices have seven CCP (Capture/Compare/PWM) modules, designated CCP4 through CCP10. All the modules implement standard Capture, Compare and Pulse-Width Modulation (PWM) modes.

Note: Throughout this section, generic references are used for register and bit names that are the same, except for an 'x' variable that indicates the item's association with the specific CCP module. For example, the control register is named CCPxCON and refers to CCP4CON through CCP10CON.

Each CCP module contains a 16-bit register that can operate as a 16-bit Capture register, a 16-bit Compare register or a PWM Master/Slave Duty Cycle register. For the sake of clarity, all CCP module operation in the following sections is described with respect to CCP4, but is equally applicable to CCP5 through CCP10.

Note: The CCP9 and CCP10 modules are disabled on the devices with 32 Kbytes of program memory (PIC18FX5K22).

REGISTER 19-1: CCPxCON: CCPx CONTROL REGISTER (CCP4-CCP10 MODULES)(1)

U-0	U-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
—	—	DCxB1	DCxB0	CCPxM3(2)	CCPxM2(2)	CCPxM1(2)	CCPxM0(2)
bit 7							bit 0

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

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

bit 5-4 **DCxB<1:0>:** PWM Duty Cycle bit 1 and bit 0 for CCPx Module

Capture mode:
Unused.

Compare mode:
Unused.

PWM mode:
These bits are the two Least Significant bits (bit 1 and bit 0) of the 10-bit PWM duty cycle. The eight Most Significant bits (DCx<9:2>) of the duty cycle are found in CCPRxL.

bit 3-0 **CCPxM<3:0>**: CCPx Module Mode Select bits(2)

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

Note 1: The CCP9 and CCP10 modules are not available on the devices with 32 Kbytes of program memory (PIC18FX5K22).

2: CCPxM<3:0> = 1011 will only reset the timer and not start A/D conversion on CCPx match.

20.0 ENHANCED CAPTURE/COMPARE/PWM (ECCP) MODULE

PIC18F87K22 family devices have three Enhanced Capture/Compare/PWM (ECCP) modules: ECCP1, ECCP2 and ECCP3. These modules contain a 16-bit register, which can operate as a 16-bit Capture register, a 16-bit Compare register or a PWM Master/Slave Duty Cycle register. These ECCP modules are upward compatible with CCP

Note: Throughout this section, generic references are used for register and bit names that are the same, except for an 'x' variable that indicates the item's association with the ECCP1, ECCP2 or ECCP3 module. For example, the control register is named CCPxCON and refers to CCP1CON, CCP2CON and CCP3CON.

ECCP1, ECCP2 and ECCP3 are implemented as standard CCP modules with enhanced PWM capabilities. These include:

- Provision for two or four output channels
- Output Steering modes
- Programmable polarity
- Programmable dead-band control
- Automatic shutdown and restart

The enhanced features are discussed in detail in **Section 20.4** "**PWM (Enhanced Mode)**".

The ECCP1, ECCP2 and ECCP3 modules use the control registers CCP1CON, CCP2CON and CCP3CON. The control registers, CCP4CON through CCP10CON, are for the modules, CCP4 through CCP10.

REGISTER 20-1: CCPxCON: ENHANCED CAPTURE/COMPARE/PWM x CONTROL

R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
PxM1	PxM0	DCxB1	DCxB0	CCPxM3	CCPxM2	CCPxM1	CCPxM0
bit 7							bit 0

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

bit 7-6 **PxM<1:0>:** Enhanced PWM Output Configuration bits

If CCPxM<3:2> = `00`, `01`, `10`:

`xx` = PxA assigned as capture/compare input/output; PxB, PxC and PxD assigned as port pins

If CCPxM<3:2> = `11`:

`00` = Single output: PxA, PxB, PxC and PxD are controlled by steering (see **Section 20.4.7** “**Pulse Steering Mode**”)
`01` = Full-bridge output forward: PxD is modulated; PxA is active; PxB, PxC is inactive
`10` = Half-bridge output: PxA, PxB are modulated with dead-band control; PxC and PxD are assigned as port pins
`11` = Full-bridge output reverse: PxB is modulated; PxC is active; PxA and PxD are inactive

bit 5-4 **DCxB<1:0>**: PWM Duty Cycle bit 1 and bit 0

Capture mode:

Unused.

Compare mode:

Unused.

PWM mode:

These bits are the two LSbs of the 10-bit PWM duty cycle. The eight MSbs of the duty cycle are found in CCPRxL.

bit 3-0 **CCPxM<3:0>**: ECCPx Mode Select bits

`0000` = Capture/Compare/PWM off (resets ECCPx module)
`0001` = Reserved
`0010` = Compare mode: toggle output on match
`0011` = Capture mode
`0100` = Capture mode: every falling edge
`0101` = Capture mode: every rising edge
`0110` = Capture mode: every fourth rising edge
`0111` = Capture mode: every 16th rising edge
`1000` = Compare mode: initialize ECCPx pin low, set output on compare match (set CCPxIF)
`1001` = Compare mode: initialize ECCPx pin high, clear output on compare match (set CCPxIF)
`1010` = Compare mode: generate software interrupt only, ECCPx pin reverts to I/O state
`1011` = Compare mode: trigger special event (ECCPx resets TMR1 or TMR3, starts A/D conversion, sets CCPxIF bit)
`1100` = PWM mode: PxA and PxC are active-high; PxB and PxD are active-high
`1101` = PWM mode: PxA and PxC are active-high; PxB and PxD are active-low
`1110` = PWM mode: PxA and PxC are active-low; PxB and PxD are active-high
`1111` = PWM mode: PxA and PxC are active-low; PxB and PxD are active-low

22.0 ENHANCED UNIVERSAL SYNCHRONOUS ASYNCHRONOUS RECEIVER TRANSMITTER (EUSART)

The Enhanced Universal Synchronous Asynchronous Receiver Transmitter (EUSART) module is one of two serial I/O modules. (Generically, the EUSART is also known as a Serial Communications Interface or SCI.) The EUSART can be configured as a full-duplex, asynchronous system that can communicate with peripheral devices, such as CRT terminals and personal computers. It can also be configured as a half-duplex synchronous system that can communicate with peripheral devices, such as A/D or D/A integrated circuits, serial EEPROMs, etc.

The Enhanced USART module implements additional features, including automatic baud rate detection and calibration, automatic wake-up on Sync Break reception and 12-bit Break character transmit. These make it ideally suited for use in Local Interconnect Network bus (LIN/J2602 bus) systems.

All members of the PIC18F87K22 family are equipped with two independent EUSART modules, referred to as EUSART1 and EUSART2. They can be configured in the following modes:

- Asynchronous (full duplex) with:
  - Auto-wake-up on character reception
  - Auto-baud calibration
  - 12-bit Break character transmission
- Synchronous - Master (half duplex) with selectable clock polarity
- Synchronous - Slave (half duplex) with selectable clock polarity

The pins of EUSART1 and EUSART2 are multiplexed with the functions of PORTC (RC6/TX1/CK1 and RC7/RX1/DT1) and PORTG (RG1/TX2/CK2/AN19/C3OUT and RG2/RX2/DT2/AN18/C3INA), respectively. In order to configure these pins as an EUSART:

- For EUSART1:
  - Bit, SPEN (RCSTA1<7>), must be set (= `1`)
  - Bit, TRISC<7>, must be set (= `1`)
  - Bit, TRISC<6>, must be cleared (= `0`) for Asynchronous and Synchronous Master modes
  - Bit, TRISC<6>, must be set (= `1`) for Synchronous Slave mode
- For EUSART2:
  - Bit, SPEN (RCSTA2<7>), must be set (= `1`)
  - Bit, TRISG<2>, must be set (= `1`)
  - Bit TRISG<1> must be cleared (= `0`) for Asynchronous and Synchronous Master modes
  - Bit, TRISC<6>, must be set (= `1`) for Synchronous Slave mode

Note: The EUSART control will automatically reconfigure the pin from input to output as needed.

The operation of each Enhanced USART module is controlled through three registers:

- Transmit Status and Control (TXSTAx)
- Receive Status and Control (RCSTAx)
- Baud Rate Control (BAUDCONx)

These are detailed on the following pages in Register 22-1, Register 22-2 and Register 22-3, respectively.

Note: Throughout this section, references to register and bit names that may be associated with a specific EUSART module are referred to generically by the use of ‘x’ in place of the specific module number. Thus, “RCSTAx” might refer to the Receive Status register for either EUSART1 or EUSART2.

REGISTER 22-1: TXSTAx: TRANSMIT STATUS AND CONTROL REGISTER

R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R-1	R/W-0
CSRC	TX9	TXEN[1]	SYNC	SENDB	BRGH	TRMT	TX9D
bit 7							bit 0

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

bit 7 **CSRC:** Clock Source Select bit

Asynchronous mode:
Don’t care.

Synchronous mode:
`1` = Master mode (clock generated internally from BRG)
`0` = Slave mode (clock from external source)

bit 6 **TX9:** 9-Bit Transmit Enable bit
`1` = Selects 9-bit transmission
`0` = Selects 8-bit transmission

bit 5 **TXEN:** Transmit Enable bit[1]
`1` = Transmit is enabled
`0` = Transmit is disabled

bit 4 **SYNC:** EUSART Mode Select bit
`1` = Synchronous mode
`0` = Asynchronous mode

bit 3 **SENDB:** Send Break Character bit

Asynchronous mode:
`1` = Send Sync Break on next transmission (cleared by hardware upon completion)
`0` = Sync Break transmission has completed

Synchronous mode:
Don’t care.

bit 2 **BRGH:** High Baud Rate Select bit

Asynchronous mode:
`1` = High speed
`0` = Low speed

Synchronous mode:
Unused in this mode.

bit 1 **TRMT:** Transmit Shift Register Status bit
`1` = TSR is empty
`0` = TSR is full

bit 0 **TX9D:** 9th bit of Transmit Data
Can be address/data bit or a parity bit.

Note 1: SREN/CREN overrides TXEN in Sync mode.

23.0 12-BIT ANALOG-TO-DIGITAL CONVERTER (A/D) MODULE

The Analog-to-Digital (A/D) Converter module in the PIC18F87K22 family of devices has 16 inputs for the 64-pin devices and 24 inputs for the 80-pin devices. This module allows conversion of an analog input signal to a corresponding 12-bit digital number.

The module has these registers:

- A/D Control Register 0 (ADCON0)
- A/D Control Register 1 (ADCON1)
- A/D Control Register 2 (ADCON2)
- A/D Port Configuration Register 0 (ANCON0)
- A/D Port Configuration Register 1 (ANCON1)
- A/D Port Configuration Register 2 (ANCON2)
- ADRESH (the upper, A/D Results register)
- ADRESL (the lower, A/D Results register)

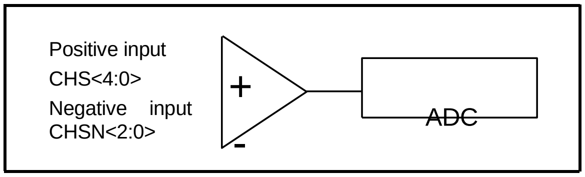
The ADCON0 register, shown in Register 23-1, controls the operation of the A/D module. The ADCON1 register, shown in Register 23-2, configures the voltage reference and special trigger selection. The ADCON2 register, shown in Register 23-3, configures the A/D clock source and programmed acquisition time and justification.

23.1 Differential A/D Converter

The converter in PIC18F87K22 family devices is implemented as a differential A/D where the differential voltage between two channels is measured and converted to digital values (see Figure 23-1).

The converter also can be configured to measure a voltage from a single input by clearing the CHSN bits (ADCON1<2:0>). With this configuration, the negative channel input is connected internally to AVSS (see Figure 23-2).

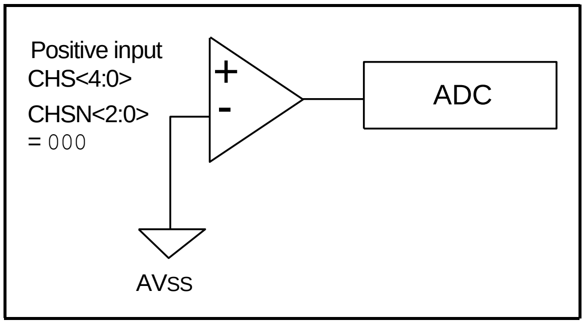
FIGURE 23-1: DIFFERENTIAL CHANNEL MEASUREMENT



Differential conversion feeds the two input channels to a unity gain differential amplifier. The positive channel input is selected using the CHS bits (ADCON0<6:2>) and the negative channel input is selected using the CHSN bits (ADCON1<2:0>).

The output from the amplifier is fed to the A/D Converter, as shown in Figure 23-1. The 12-bit result is available on the ADRESH and ADRESL registers. An additional bit indicates if the 12-bit result is a positive or negative value.

FIGURE 23-2: SINGLE CHANNEL MEASUREMENT



In the single-channel measurement mode, the negative input is connected to AVSS by clearing the CHSN bits (ADCON1<2:0>).

23.2 A/D Registers

23.2.1 A/D CONTROL REGISTERS

REGISTER 23-1: ADCON0: A/D CONTROL REGISTER 0

U-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
—	CHS4	CHS3	CHS2	CHS1	CHS0	GO/$\overline{\text{DONE}}$	ADON
bit 7							bit 0

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

bit 7 **Unimplemented:** Read as ‘0’

bit 6-2 **CHS<4:0>:** Analog Channel Select bits

00000 = Channel 00 (AN0)
00001 = Channel 01 (AN1)
00010 = Channel 02 (AN2)
00011 = Channel 03 (AN3)
00100 = Channel 04 (AN4)
00101 = Channel 05 (AN5)
00110 = Channel 06 (AN6)
00111 = Channel 07 (AN7)
01000 = Channel 08 (AN8)
01001 = Channel 09 (AN9)
01010 = Channel 10 (AN10)
01011 = Channel 11 (AN11)
01100 = Channel 12 (AN12)(1,2)
01101 = Channel 13 (AN13)(1,2)
01110 = Channel 14 (AN14)(1,2)
01111 = Channel 15 (AN15)(1,2)
10000 = Channel 16 (AN16)
10001 = Channel 17 (AN17)
10010 = Channel 18 (AN18)
10011 = Channel 19 (AN19)
10100 = Channel 20 (AN20)(1,2)
10101 = Channel 21 (AN21)(1,2)
10110 = Channel 22 (AN22)(1,2)
10111 = Channel 23 (AN23)(1,2)
11000 = (Reserved)(2)
11001 = (Reserved)(2)
11010 = (Reserved)(2)
11011 = (Reserved)(2)
11100 = Channel 28 (Reserved CTMU) 11101 =
Channel 29 (Internal temperature diode) 11110 =
Channel 30 (V_{DDCORE})
11111 = Channel 31 (v1.024V band gap)

bit 1 **GO/$\overline{\text{DONE}}$:** A/D Conversion Status bit

1 = A/D (or calibration) cycle in progress. Setting this bit starts an A/D conversion cycle. The bit is cleared automatically by hardware when the A/D conversion is completed.
0 = A/D conversion completed or not in progress

bit 0 **ADON:** A/D On bit

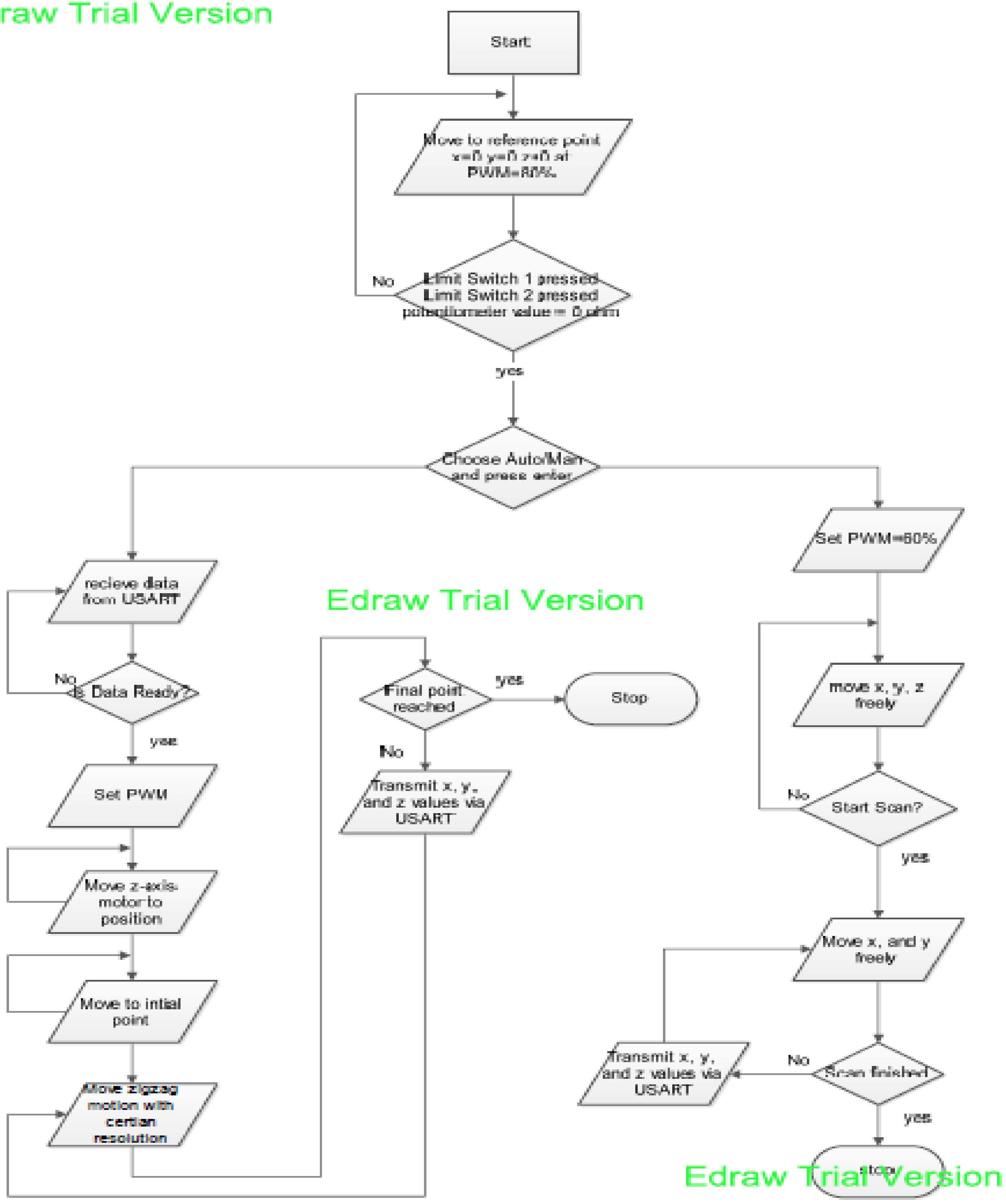
1 = A/D Converter is operating
0 = A/D conversion module is shut off and consuming no operating current

Note 1: These channels are not implemented on 64-pin devices.
2: Performing a conversion on unimplemented channels will return random values.

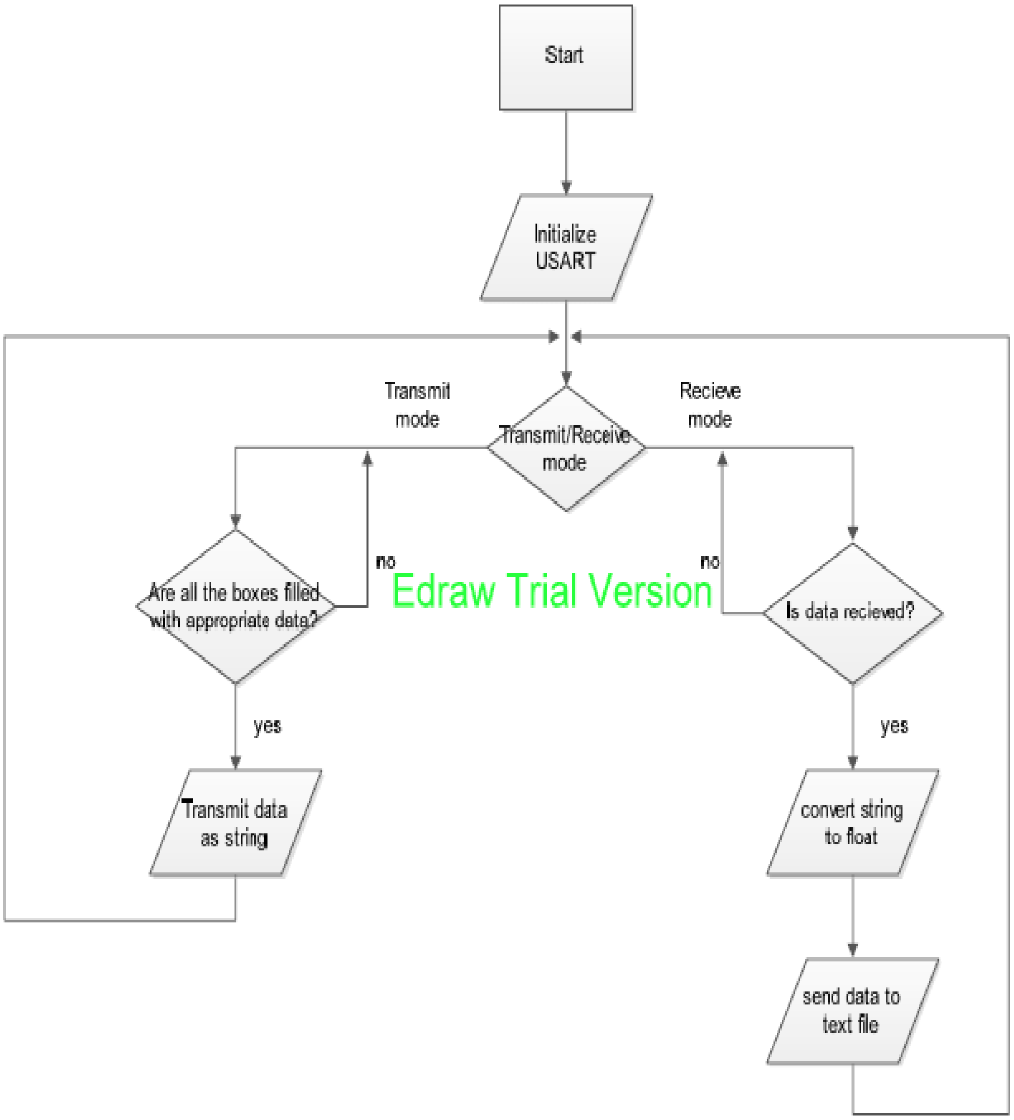
Appendix III

Software and Guided User Interface

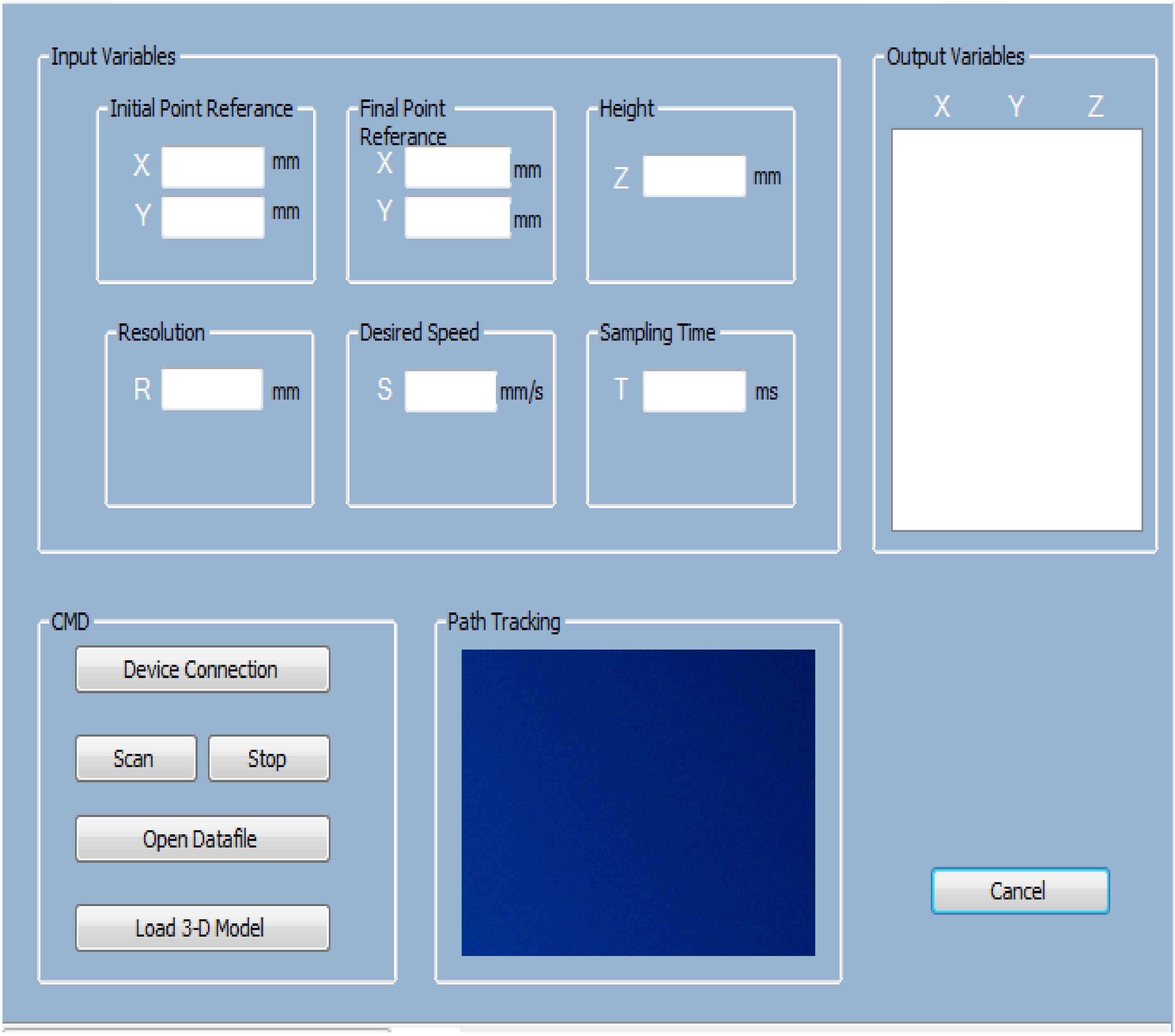
PIC Flowchart



Visual basic Flowchart



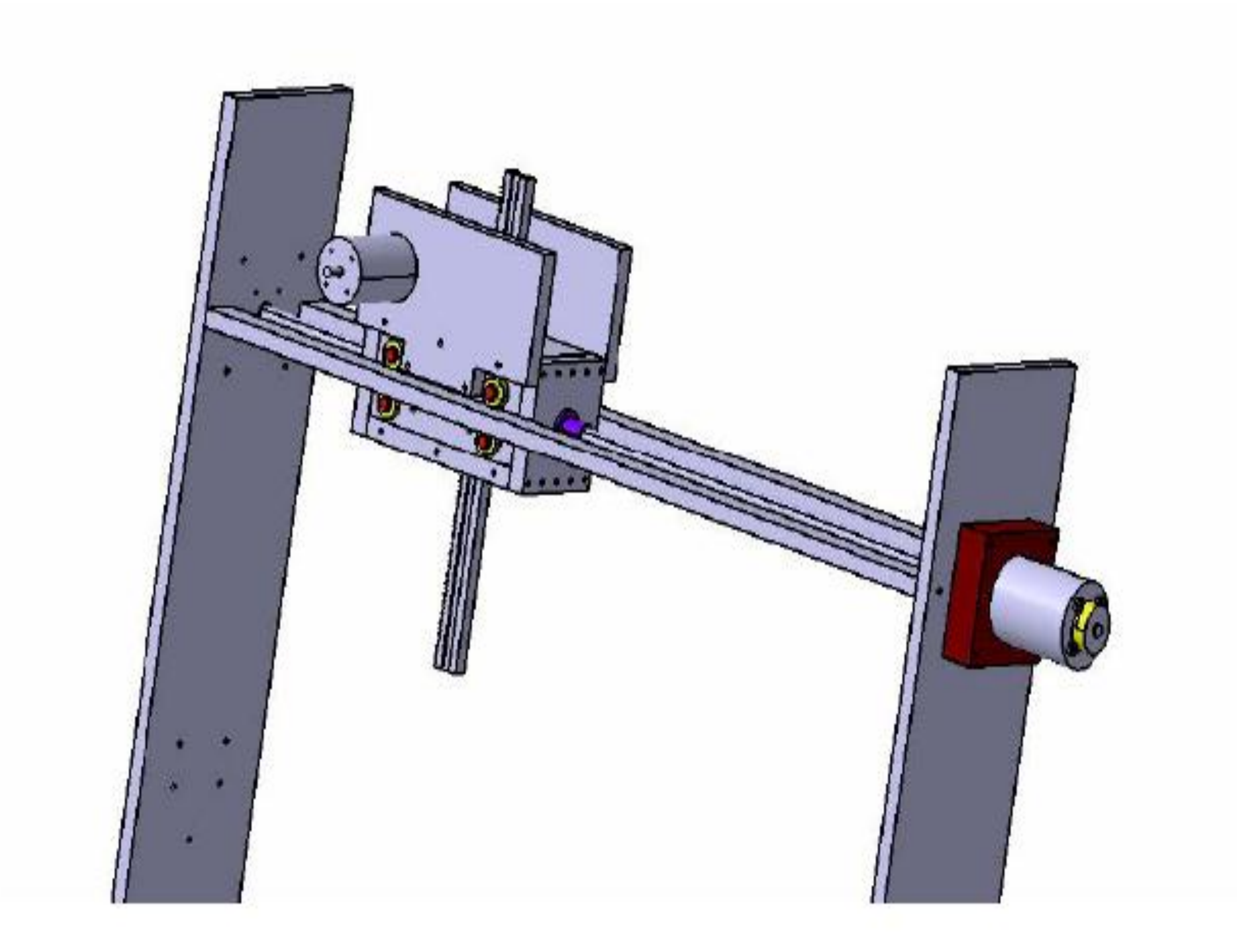
Automatic mode guided user interface



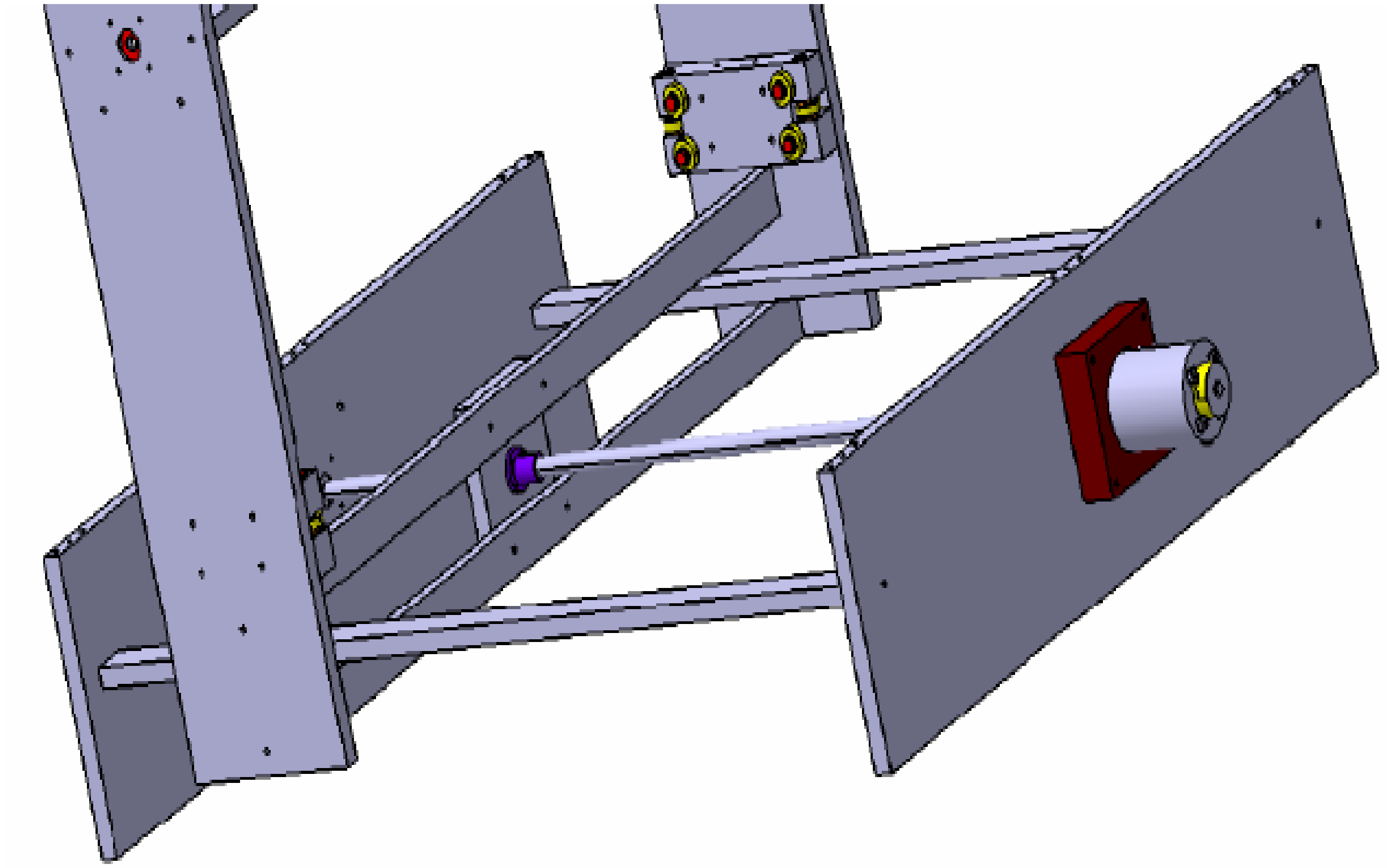
Appendix V

CAD Design

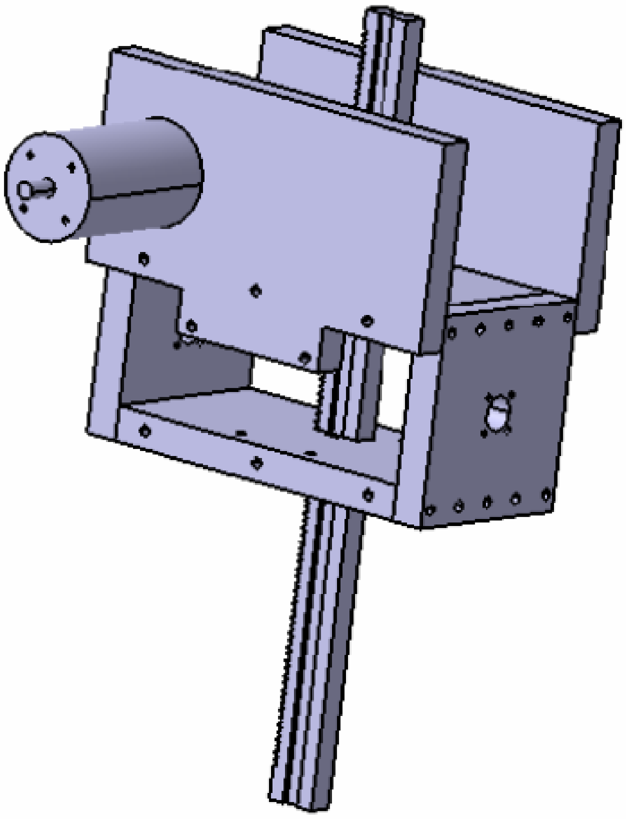
Y- axis assembly



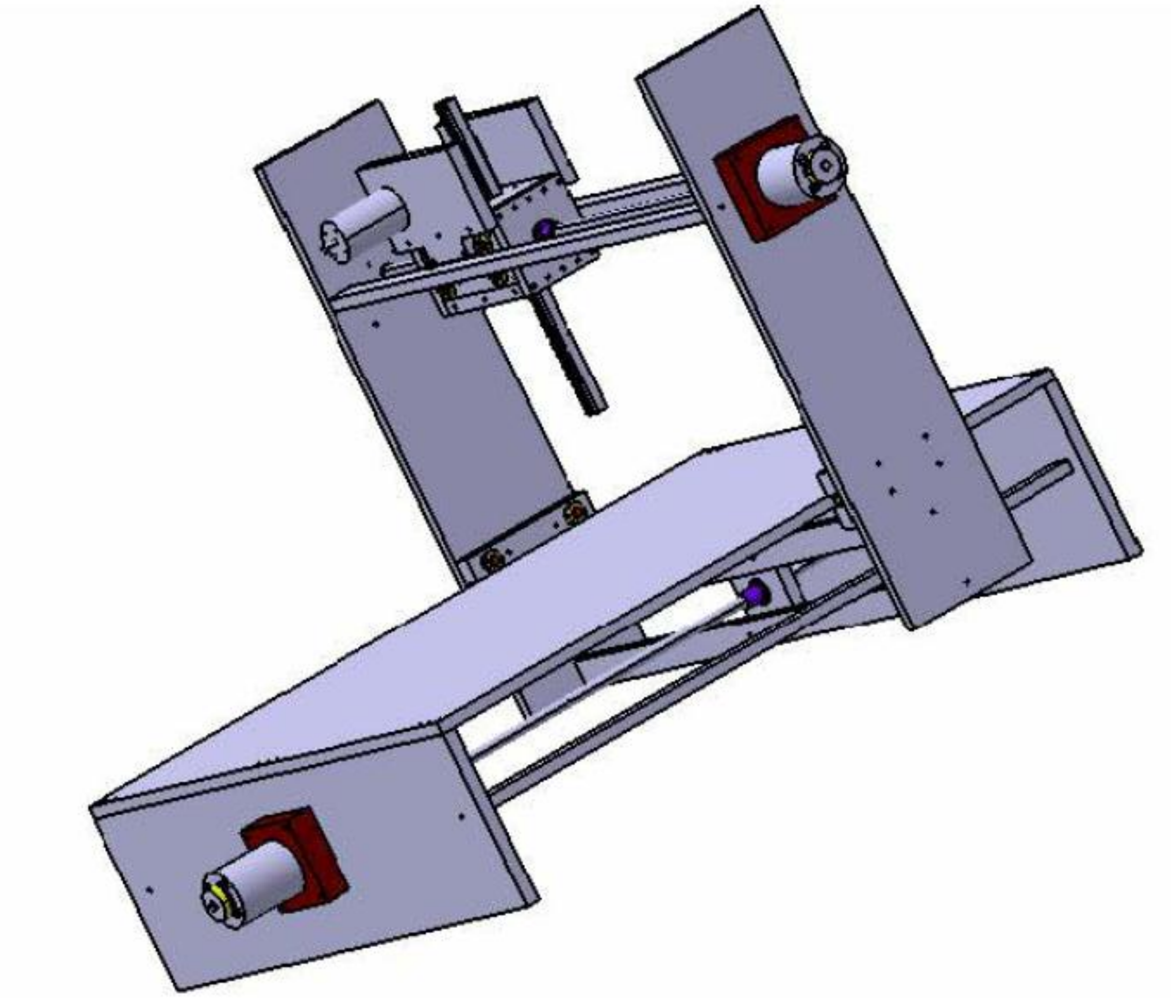
X- axis assembly



Z- axis assembly



Body Structure

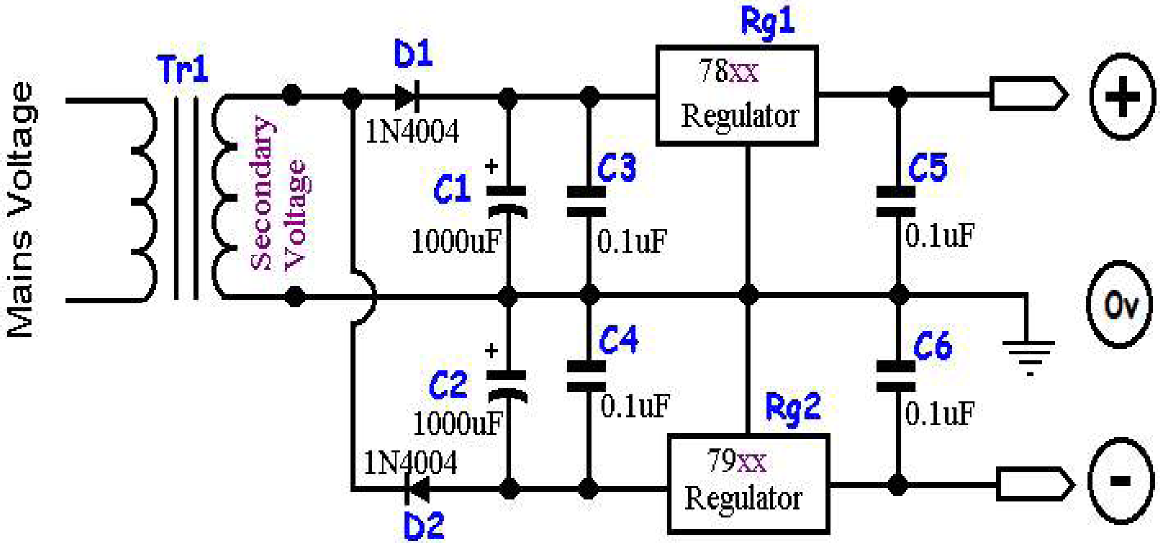


Appendix IV

Electronic Schematics

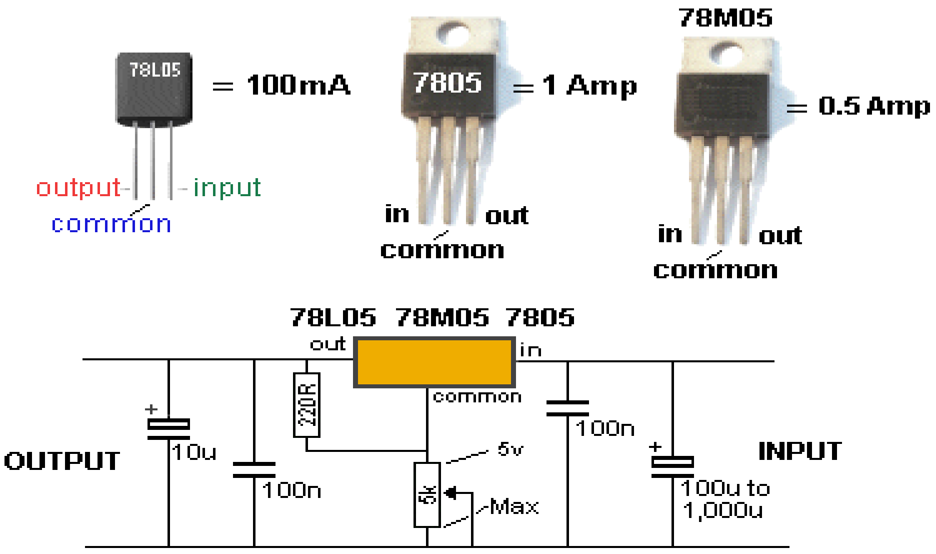
Bipolar Circuits:

Bipolar circuit is used to drive the Op-amp that refines the signal from the optical sensor to the microcontroller.



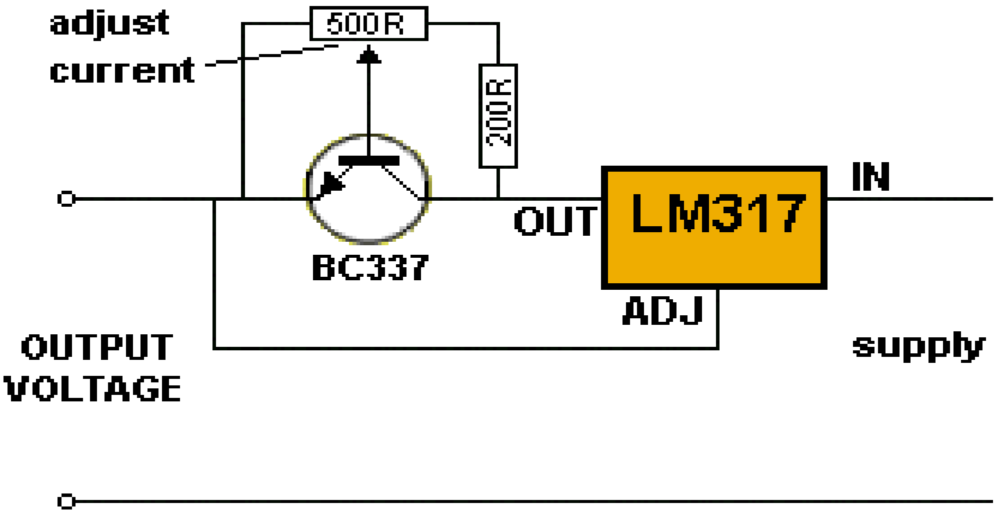
Power Circuit:

The following figure, shows adjustable power supply circuit ,it take a 24v dc and gives 5-30 volt in its output terminals .We used it in order to supply the microcontroller, the optical sensor, and the encoders of servo motors.

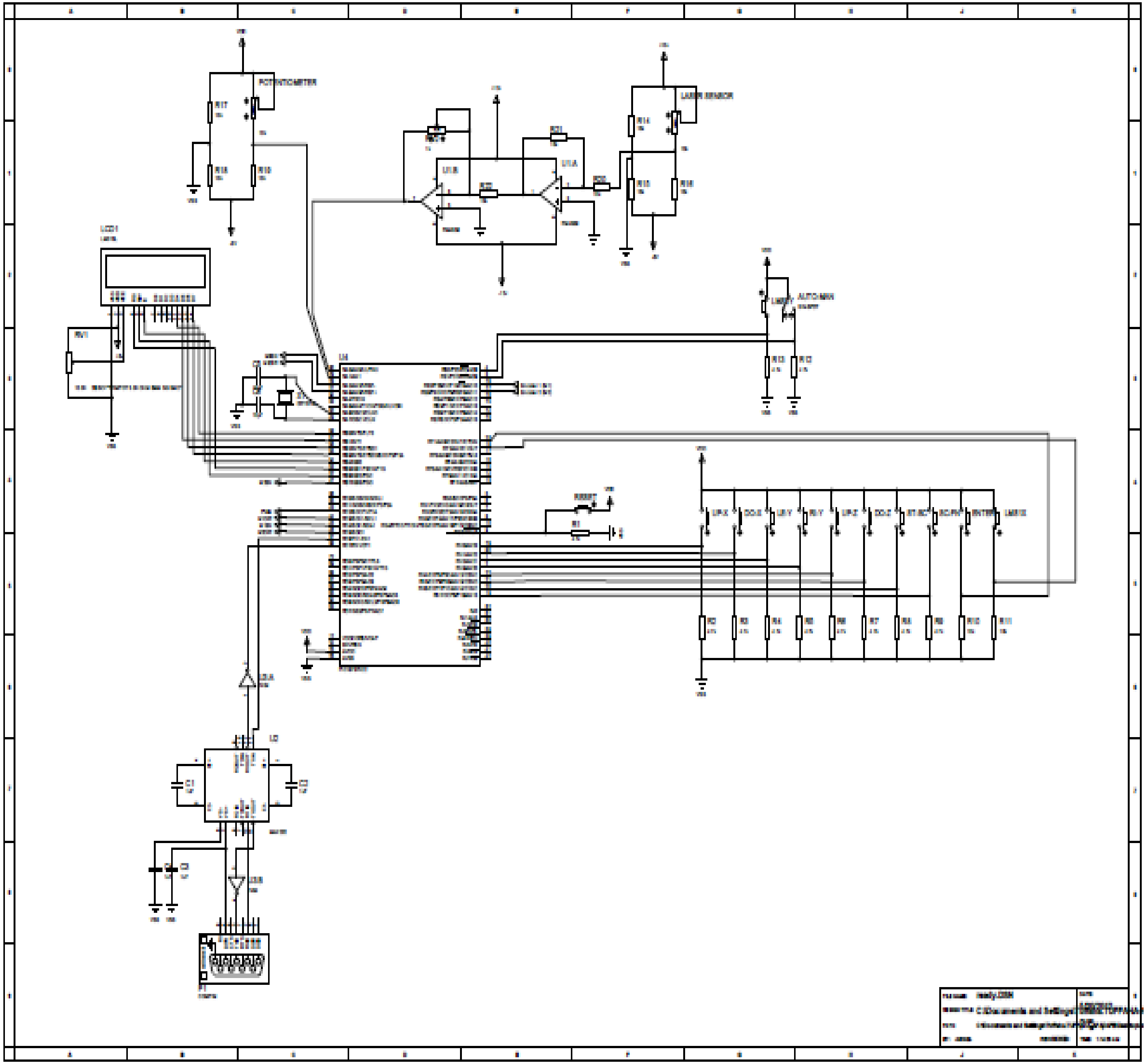


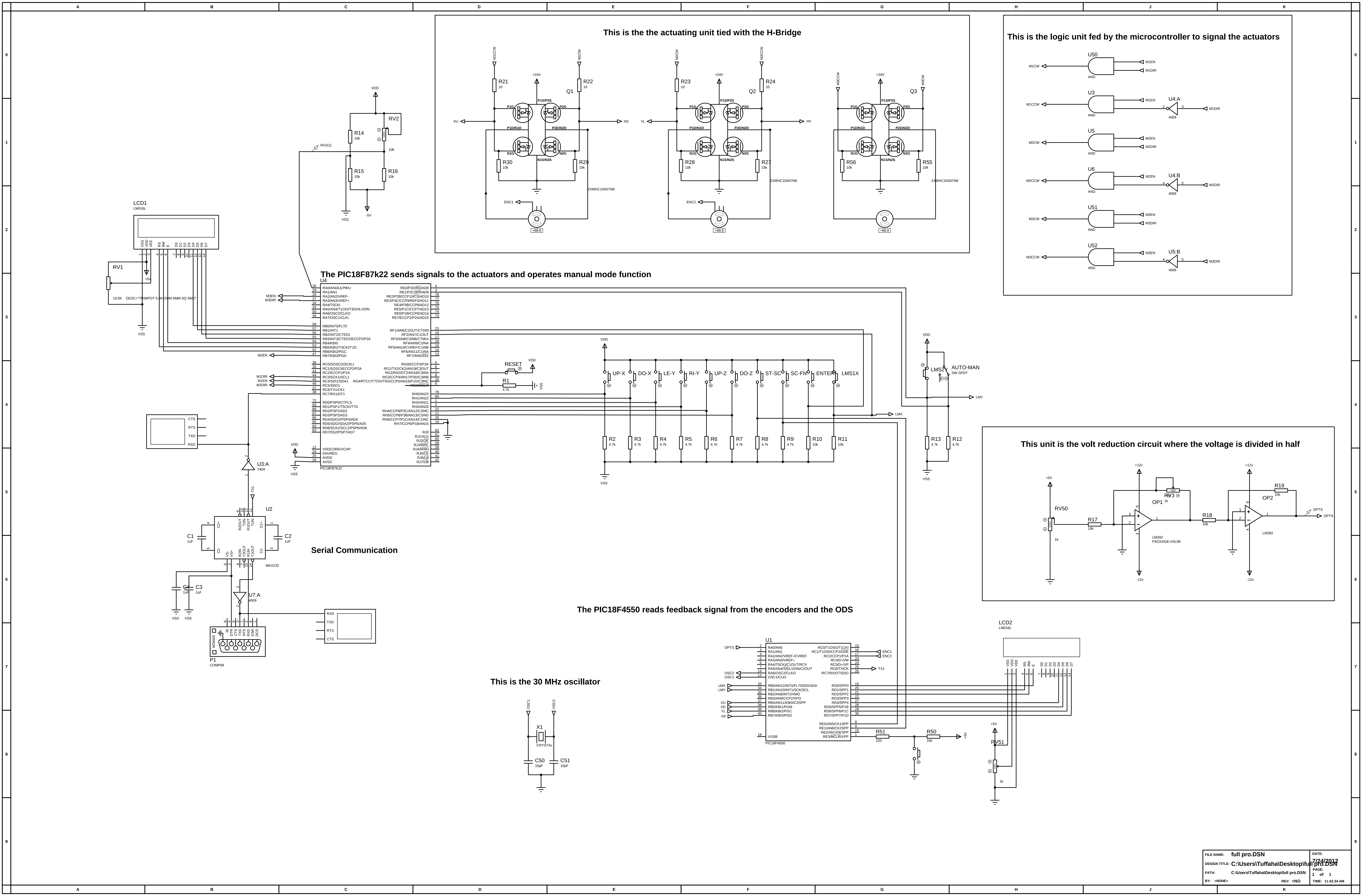
Current Limiter Circuit:

The current limiter circuit is used to limit the current flows to another circuits such the optical sensor is need a less than 25mA current for opening circuit.



PIC microcontroller interfacing circuit:





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