DEVELOPMENT OF A 3 AXES PC NUMERICAL CONTROL SYSTEM FOR INDUSTRIAL APPLICATIONS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
THE MIDDLE EAST TECHNICAL UNIVERSITY

BY

FEZA BAŞAR

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN
THE DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

SEPTEMBER 2003

Approval of the Graduate School of Natural and Applied Sciences

_____

Prof. Dr. Canan Özgen
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

_____

Prof. Dr. Mübeccel Demirekler
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

_____

Prof. Dr. Mirzahan Hızal
Supervisor

Examining Committee Members

Prof. Dr. Ahmet Rumeli _____

Prof. Dr. Muammer Ermiş _____

Prof. Dr. Mirzahan Hızal _____

Prof. Dr. Nevzat Özay _____

M.Sc. Abdullah Nadar _____

ABSTRACT

DEVELOPMENT OF A 3 AXES PC NUMERICAL CONTROL SYSTEM FOR INDUSTRIAL APPLICATIONS

BAŞAR, Feza
M.Sc. , Department of Electrical and Electronics Engineering
Supervisor: Prof. Dr. Mirzahan Hızal

September 2003, 96 Pages

In this study, a three-axes PC numerical control system for industrial applications has been developed. With this system, fast and cheap prototyping of designed objects can be realized. The system consists of software and a hardware which includes an XYZ positioning table and three step motors controlling this table. A proper drive circuit for the stepper motors is utilized. The software digitizes two dimensional drawings of three dimensional objects and generates the control signals for the XYZ positioning table.

The software is developed under Microsoft Studio Visual Basic 6.0 environment regardless of the OS of the PC. The parallel port of the PC has been utilized for generating the necessary control signals for the stepper motors.

Keywords: Machine Tool, Step Motor, Motion Control, Parallel Port Programming, Step Motor Drive

ÖZ

ENDÜSTRİYEL AMAÇLI 3 EKSENLİ BİR BİLGİSAYAR SAYISAL KONTROL SİSTEMİNİN GELİŞTİRİLMESİ

BAŞAR, Feza
Yüksek Lisans , Elektrik-Elektronik Mühendisliği Bölümü
Tez Yöneticisi: Prof. Dr. Mirzahan Hızal

Eylül 2003, 96 sayfa

Bu çalışmada endüstriyel amaçlı üç eksenli bir bilgisayar sayısal kontrol sistemi geliştirilmiştir. Bu sistemle tasarlanan objelerin hızlı ve ucuz prototipleri gerçekleştirilebilir. Sistem bir yazılım ve XYZ ekseninde hareket eden tezgahtan ve bu tezgahı kontrol eden üç adet adımlı motordan oluşmaktadır. Adımlı motorlar için uygun bir sürücü devresi kullanılmıştır. Yazılım ise iki boyutlu olarak modellenen üç boyutlu nesneleri sayısallaştırıp tezgah için gerekli kontrol işaretlerini üretmektedir.

Yazılım bilgisayarın işletim sisteminden bağımsız olarak Microsoft Studio Visual Basic 6.0 ortamında geliştirilmiştir. Adımlı motorların gerekli kontrol işaretleri bilgisayarın paralel kanalının kullanılması ile oluşturulmaktadır.

Anahtar Kelimeler: Tezgah, Adımlı Motor, Hareket Kontrol, Paralel Kanal Programlama, Adımlı Motor Sürücüsü

to my beloved husband Çağrı,

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to Prof. Dr. Mirzahan Hızal for his encouragements, guidance and supervision.

Special thanks to my pet Pisigül for her great interest in my papers.

Finally, I would like to thank my beloved husband Çağrı for his precious help, great support and understanding. I believe without him this thesis would not have been completed.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BMP : Bit Map

CAD : Computer Aided Design

DC : Direct Current

I/O : Input/Output

JPG : Joint Photographers Experts Group

OS : Operating System

LOC : Lines of Code

PC : Personal Computer

IC : Integrated Circuit

GUI : Graphical User Interface

TIFF : Tagged Image File Format

CHAPTER 1

INTRODUCTION

The efficiency of the industrial applications has increased enormously with the introduction of the computers to the processes. Computers have started to take place in every single point in the industry enhancing the development and manufacturing stages. One of the important areas of interest in the application of computers is the “Computer Aided Design” (CAD) followed by implementation and production stages.

CAD can be efficiently used for prototyping issues in industrial applications. A proper prototyping machine tool with specially designed CAD program will decrease the time for design and implementation of prototypes.

The three-dimensional objects can be represented in the CAD applications by various methods. One method is to show a three dimensional object represented by three views which are drawn from “Front”, “Left” and “Top” [1]. The advantage of this method is that no information on the object is ambiguous so that the object is totally represented by the drawing, but this method requires intensive care while drawing the object and requires specially trained technicians.

Another method for representing the three dimensional objects is using two dimensional models where only the top view is sufficient. In this method, the depth information is kept in an algorithm or a color pattern. It is obvious that, an object as

shown in Figure 1.1 cannot be represented by this method. But the advantage of this method is ease of generating the views and the digital image of the object.

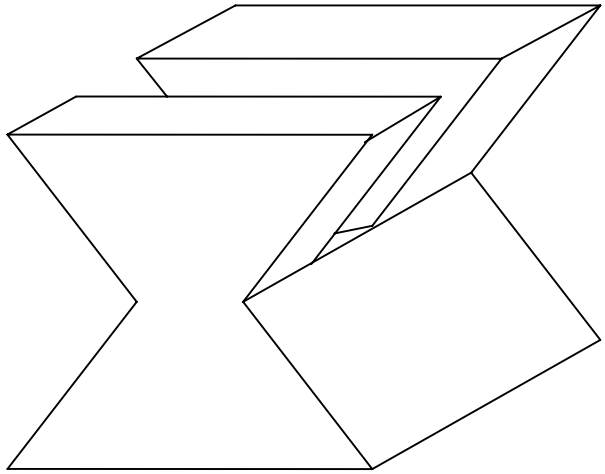


Figure 1.1 An object that cannot be represented by only one two-dimensional view

In the industry, various motion control tools are used widely but among these, step motors are one of the easiest to be applied and cheapest to be purchased. The simple drive circuits can easily be controlled via digital signals which enable full control over a regular PC. By the application of these motors, an XYZ positioning system can easily be constructed and furthermore this machine tool will be easily controlled via a PC.

In this study, a CAD program has been developed to recognize objects from standard image files (BMP, JPG, TIFF, etc.) that contain only top view. This method accelerates the digitizing process of the objects with respect to the modeling with three views.

The program generates the necessary control signals for a specially designed three-axes positioning table that is controlled by three step motors. The step motors' movements are based on the digitizing process i.e. the motors follow the path that is

specified by the digitizing process resulting in fast response of the system. The motors never move on points that will never be drilled. Furthermore, all points having the same depth level are drilled consequently which lead to smooth shape of the drilled object as well as saving time.

The software has been developed under Microsoft Studio Visual Basic 6.0 environment. This tool has been chosen because of its superior properties and ease of programming. The system requires no extra hardware except the three axes XYZ positioning table and so the cost of the system is decreased. The parallel port of the PC has been utilized for sending the necessary control signals for the stepper motors. An ActiveX based special interface software for the parallel port is used to free the software of the OS of the PC.

The organization of the thesis is as follows:

- In Chapter 2, general properties, types, operation principles, modes, driver circuits, characteristics and control types of step motors are given. The advantages of using step motors are discussed.
- In Chapter 3, the hardware and software solutions are introduced and GUI based programming languages and definitions about image processing are discussed.
- In Chapter 4, the image requirements specifications are given. The software modules and their tasks are explained and analyzed in detail.
- In Chapter 5, the image processing and drilling performances are analyzed and the drilled samples are given.
- In Chapter 6, the final conclusions on this study are made and the further work on this area is proposed.

CHAPTER 2

STEPPING MOTORS

A stepping motor is a permanent magnet or variable reluctance dc motor that has the following performance characteristics:

- rotation in both directions,
- precision angular incremental changes,
- repetition of accurate motion or velocity profiles,
- a holding torque at zero speed, and
- capability for digital control.

It is an electromechanical device which converts electrical pulses into discrete mechanical movements. Basically, it is a synchronous motor with the magnetic field electronically switched to rotate the armature magnet around. The shaft or spindle of a stepper motor rotates in discrete step increments when electrical command pulses are applied to it in the proper sequence.

The number and rate of the pulses control the position and speed of the motor shaft. The motor rotation has several direct relationships to these applied input pulses. The sequence of the applied pulses is directly related to the direction of motor shafts rotation. The speed of the motor shaft's rotation is directly related to the frequency of the input pulses and the length of rotation is directly related to the number of input pulses applied. Generally, stepping motors are manufactured with

steps per revolution of 12, 24, 72, 144, 180, and 200, resulting in shaft increments of 30, 15, 5, 2.5, 2, and 1.8 degrees per step.

Theoretically, a stepping motor is a marvel in simplicity. They are very reliable at low cost, since there are no brushes or contacts in the motor. Therefore the life of the motor is simply dependent on the life of the bearing. The rotation angle of the motor is proportional to the input pulse and the motor has full torque at standstill if the windings are energized.

Stepping motors have precise positioning and repeatability of movement since good stepper motors have an accuracy of 3 – 5% of a step and this error is non cumulative from one step to the next. They give excellent responses to starting/stopping/reversing actions and it is possible to achieve very low speed synchronous rotation with a load that is directly coupled to the shaft. Also, there is a wide range of rotational speeds that can be realized as the speed is proportional to the frequency of the input pulses. Besides all these advantages, resonances that can occur and the difficulty of operation at high speeds are the disadvantages of using a stepping motor.

Stepping motors are either bipolar, requiring two power sources or a switchable polarity power source, or unipolar, requiring only one power source. They are powered by DC current sources and require digital circuitry to produce the coil energizing sequences for rotation of the motor. Feedback is not always required for control, but the use of an encoder or other position sensors can ensure accuracy when it is essential. Generally, stepping motors produce less than one horsepower (746W) and therefore they are frequently used in low-power position control applications. A stepper motor can be a good choice whenever controlled movement is required. They can be used to advantage in applications where you need to control rotation angle, speed, position and synchronism.

2.1 Stepping Motor Types

There are basically two types of motors as permanent magnet and variable reluctance stepping motors and the hybrid type of these two basic ones. They differ in terms of construction based on the use of permanent magnets and/or iron rotors with laminated steel stators. The type of the motor determines the type of the circuit driver and the type of the translator to be used.

2.1.1 Permanent Magnet Motors

The permanent magnet motor has, as the name implies, a permanent magnet rotor. It is a relatively low speed, low torque device with large step angles of either 45 or 90 degrees. Its simple construction and low cost make it an ideal choice for non industrial applications.

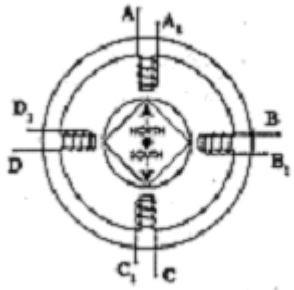


Figure 2.1 Permanent Magnet Motor

Unlike the other stepping motors, the permanent magnet motor's rotor has no teeth and is designed to be magnetized at a right angle to its axis. The permanent magnet motor shown in Figure 2.1 is a simple, 90 degree permanent magnet motor with four phases (A-D). Applying current to each phase in sequence will cause the rotor to rotate by adjusting to the changing magnetic fields. Although it operates at fairly low speed the permanent magnet motor has a relatively high torque characteristic.

2.1.2 Variable Reluctance Motors

The variable reluctance motor does not use a permanent magnet. As a result, the motor rotor can move without constraint or “detent” torque. This type of construction is good in non industrial applications that do not require a high degree of motor torque, such as the positioning of a micro slide .

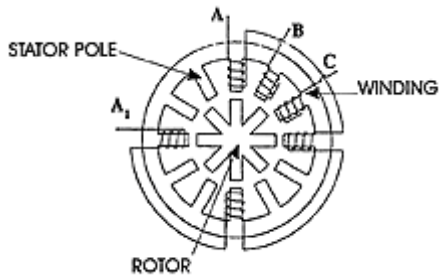


Figure 2.2 Variable Reluctance Motor

The variable reluctance motor in Figure 2.2 has four "stator pole sets" (A, B, C,), set 15 degrees apart. Current applied to pole A through the motor winding causes a magnetic attraction that aligns the rotor (tooth) to pole A. Energizing stator pole B causes the rotor to rotate 15 degrees in alignment with pole B. This process will continue with pole C and back to A in a clockwise direction. Reversing the procedure (C to A) would result in a counterclockwise rotation.

2.1.3 Hybrid Motors

Hybrid motors combine the best characteristics of the variable reluctance and permanent magnet motors. They are constructed with multi-toothed stator poles and a permanent magnet rotor. Standard hybrid motors have two hundred rotor teeth and rotate at 1.80 step angles. Other hybrid motors are available in 0.9 and 3.6 degrees step angle configurations. As they exhibit high static and dynamic torque and run at

very high step rates, hybrid motors are used in a wide variety of industrial applications.

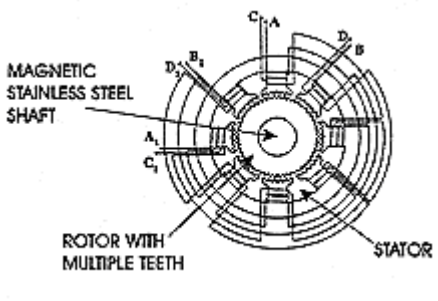


Figure 2.3 Hybrid Motor

2.1.4 Comparison of Motor Types

Variable-reluctance motors have two important advantages when the load must be moved a considerable distance. Firstly, typical step lengths are longer than in the hybrid type so less steps are required to move a given distance. A further advantage is that it has a lower rotor mechanical inertia than the hybrid and permanent-magnet types, as there is no permanent-magnet on its rotor.

Hybrid motors have a small step length which can be a great advantage when high resolution angular positioning is required. The torque producing capability for a given motor volume is greater in the hybrid than in the variable-reluctance motor. Therefore, a hybrid motor is obviously a better choice, compared with the variable reluctance one, for applications requiring a small step length and high torque in a restricted working space. When the winding of the hybrid motor are unexcited the magnet flux produces a small detent torque which retains the motor at the step position. Although the detent torque is less than the motor torque with one or more windings fully excited, it can be a useful feature where the rotor position must be preserved during a power failure.

The permanent-magnet stepping motor has a similar stator construction to the single-stack variable reluctance type, but the rotor is not toothed and is composed of

permanent magnet material. It is difficult to manufacture a small permanent-magnet rotor with a large number of poles and consequently stepping motors of this type are restricted to step lengths in the range 30-90 degrees.

2.2 Stepping Motor Winding Types

Stepping motors are classified as unifilar and bifilar according to the winding number per stator pole.

2.2.1 Unifilar Winding

Unifilar, as the name implies, has only one winding per stator pole. Stepper motors with a unifilar winding will have 4 lead wires. The wiring diagram in Figure 2.4 illustrates a typical unifilar motor:

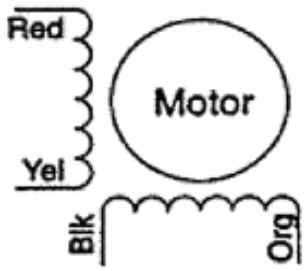


Figure 2.4 4-Lead Unifilar Motor

2.2.2 Bifilar Winding

Bifilar wound motor means that there are two identical sets of windings on each stator pole. This type of winding configuration simplifies operation in that transferring current from one coil to another one, wound in the opposite direction, will reverse the rotation of the motor shaft. Whereas, in a unifilar application, to change direction requires reversing the current in the same winding.

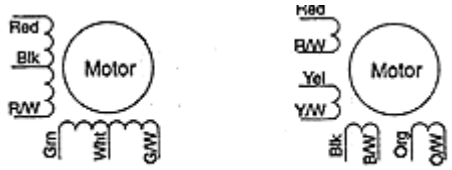


Figure 2.5 6 and 8-Lead Bifilar Motors

The most common wiring configuration for bifilar wound stepping motors is 8 leads because they offer the flexibility of either a series or parallel connection. There are however, many 6 lead stepping motors available for series connection applications.

2.3 Stepping Modes

The most common drive modes of the stepping motors are wave drive (1 phase on), full step drive (2 phases on), half step drive (1 & 2 phases on) and microstepping (continuously varying motor currents).

In wave drive mode, only one winding is energized at any given time. The disadvantage of this drive mode is that it is not possible to get the maximum output torque from the motor.

In full step drive mode, two phases are energized at any given time. It offers the simplest control electronics and it is recommended for high- and medium-frequency operation. At these frequencies, the inertia of the motor and the load smooth out the torque, resulting in less vibration and noise compared to low-speed operation.

Half stepping with 140% 1-phase-on current gives smoother movement at low step rates compared to full stepping and can be used to lower resonances at low speeds. Half stepping also doubles the system resolution. Compared to the full stepping, there is a slightly-higher torque at low speed and a small decrease at higher

step rates. The main advantage is the lowered noise and vibrations at low stepping rates. If maximum performance at both low and high step rates is essential, a switch to full-step mode can be done at a suitable frequency.

In microstepping drive the currents in the windings are continuously varying to be able to break up one full step in many smaller discrete steps. The smoothest movements at low frequencies are achieved with microstepping and higher resolution is also offered. If resonance-free movement at low step rates is important, the microstepping driver is the best choice. Microstepping can also be used to increase stop position accuracy beyond the normal motor limits.

2.4 Drive Circuits

The stepper motor driver receives low-level signals from the indexer or control system and converts them into electrical (step) pulses to run the motor. One step pulse is required for every step of the motor shaft. This process is shown in Figure 2.6.

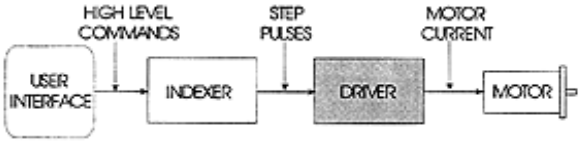


Figure 2.6 Drive circuit scheme

Speed and torque performance of the step motor is based on the flow of current from the driver to the motor winding. The factor that inhibits the flow, or limits the time it takes for the current to energize the winding, is known as inductance. The lower the inductance, the faster the current gets to the winding and the better the performance of the motor. To reduce inductance, most types of driver circuits are designed to supply a greater amount of voltage than the motors rated voltage.

The stepper motor driver circuit has two major tasks:

- To change the current and flux direction in the phase windings
- To drive a controllable amount of current through the windings, and enabling as short current rise and fall times as possible for good high speed performance.

Stepping of the stepper motor requires a change of the flux direction independently in each phase. The direction change is done by changing the current direction. It may be done in two different ways, using a bipolar or a unipolar drive.

Bipolar drive refers to the principle where the current direction in one winding is changed by shifting the voltage polarity across the winding terminals. The bipolar drive method requires one winding per phase. A two-phase will have two windings and accordingly four connecting leads. One phase of a transistor bridge bipolar drive circuit is given in Figure 2.7 [2].

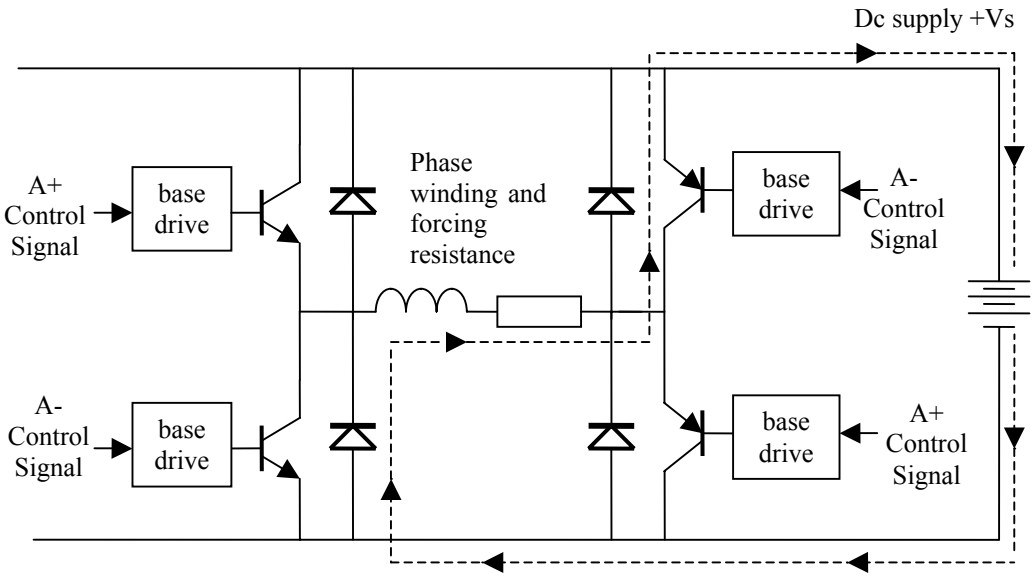


Figure 2.7 One phase of a transistor bridge bipolar drive circuit

The unipolar drive principle requires a winding with a center-tap or two separate windings per phase. Flux direction is reversed by moving the current from one half of the winding to the other half. This method requires only two switches per phase. On the other hand, the unipolar drive utilizes only half the available copper volume of the winding. Power loss in the winding is therefore twice the loss of a bipolar drive at the same output power. The three-phase unipolar drive circuit is given in Figure 2.8 [2].

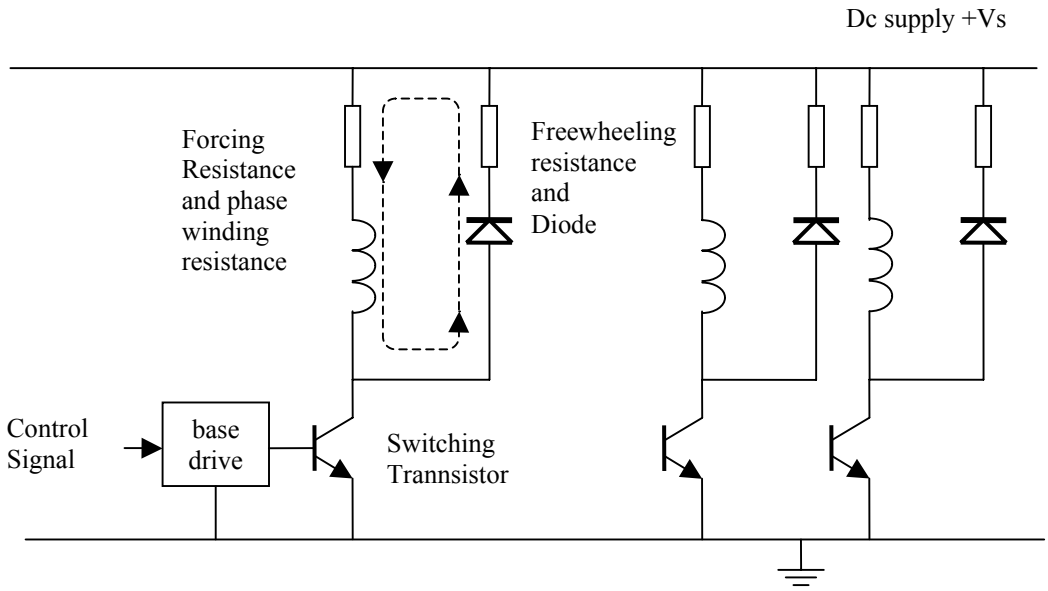


Figure 2.8 Three phase unipolar drive circuit

2.5 Static Torque Characteristics

The static torque/rotor characteristic, that shows the torque developed by the motor as a function of rotor position for several values of winding current, supply the information about the torque producing capability of a stepping motor. A typical static torque/rotor position characteristic at various currents is shown in Figure 2.9.[2] When the step motor is energized and with its rotor at the equilibrium position i.e. the step position, no torque is developed on the rotor shaft. When the rotor is displaced from the equilibrium position, a restoring torque, that is called

static holding torque, is developed which tends to restore the rotor to its stable equilibrium position. [3]

In general, the shape of the torque/rotor curves depend on the construction of the motor as well as the way the motor is excited.

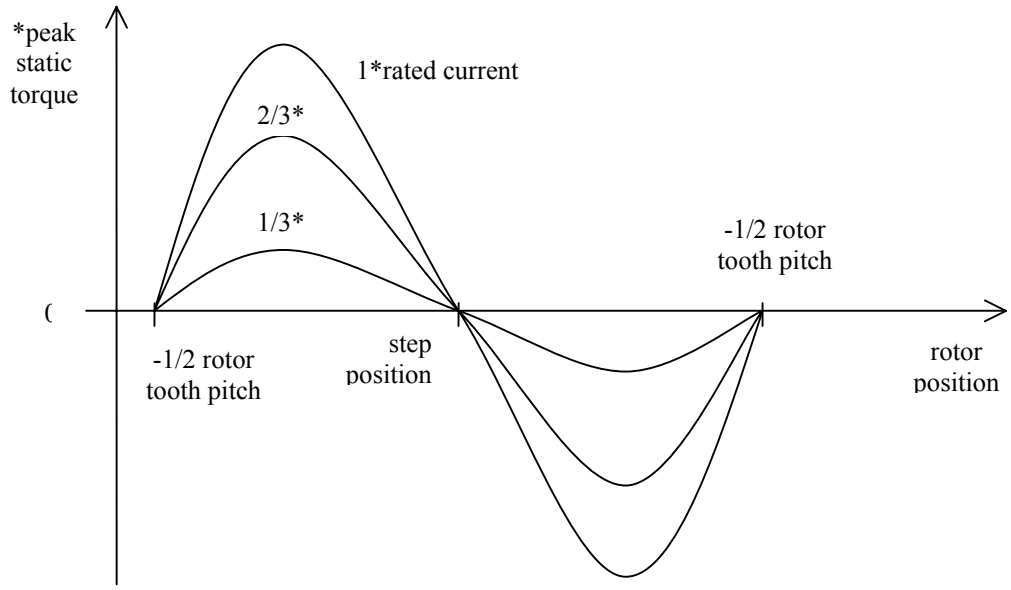


Figure 2.9 Static torque/rotor position characteristics at various currents

If the displacement is more than half a rotor tooth pitch, the equilibrium is at a distance which is a multiple of the rotor tooth pitch from the required step position. (See Figure 2.10)

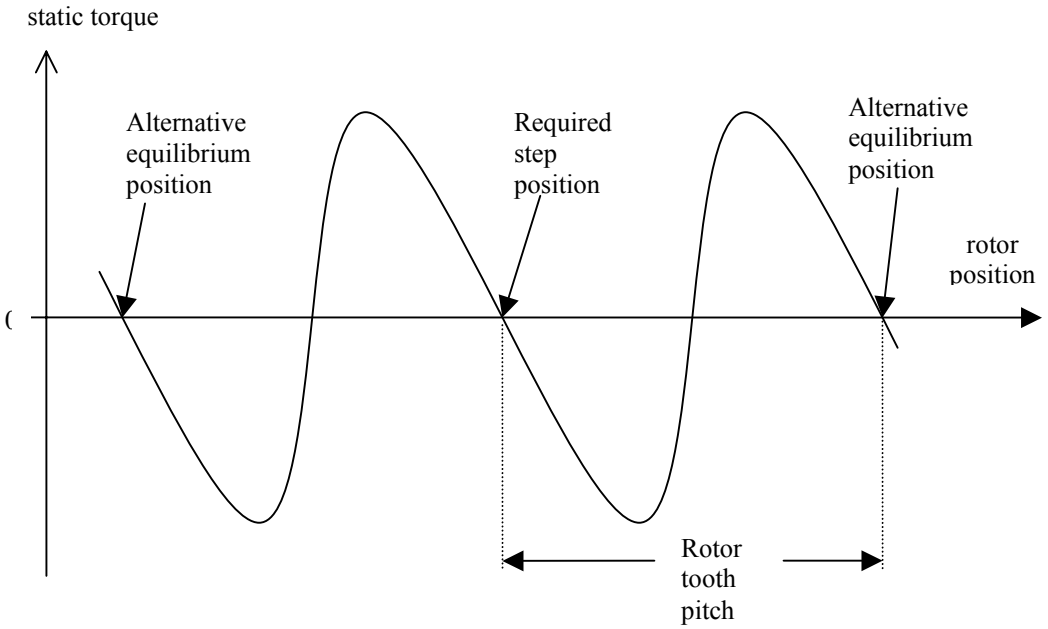


Figure 2.10 Static torque/rotor position characteristics at rated phase currents

The phase windings of both hybrid and variable reluctance stepping motors are electrically isolated and each phase is excited by a separate drive circuit, so it is possible to excite several phases at any time. When the static torque/rotor characteristics for one-phase and two-phases on excitation in Figure 2.11(a) and (b) are compared, it is apparent that they are still sinusoidal. The excitation of a three phase variable reluctance motor with two phases on rather than one phase on, has the benefit of reducing the static position error, which results from the displacement of the rotor by a small angle from the expected step position because of the torque developed by the motor to balance the load torque. This can be confirmed analytically with the following formulations. The torque equations for each phase for the static torque/rotor position characteristics of Figure 2.11(a) are

$$\begin{aligned} T_A &= -T_{PK}\sin(p\theta) \\ T_B &= -T_{PK}\sin(p\theta - 2\pi/3) \\ T_C &= -T_{PK}\sin(p\theta - 4\pi/3) \end{aligned} \tag{2.1}$$

and the resultant torque equations for “phase A + phase B” and “phase B + phase C” for the static torque/rotor position characteristics of Figure 2.11(b), that are simply obtained by summing the corresponding phase torque expressions, are

$$\begin{aligned} T_{AB} &= T_A + T_B = -T_{PK} \sin(p\theta - \pi/3) \\ T_{BC} &= T_B + T_C = -T_{PK} \sin(p\theta - \pi) \end{aligned} \tag{2.2}$$

It is obvious that the both graphical and analytical results indicate that the only difference between the excitation schemes is in the equilibrium positions.

An alternative method for minimizing the static position error is to connect the motor to the load by a gear.

It is true that the excitation of several phases improves the torque produced, but in applications where the available power is limited to drive the motor, it should be considered that the more power is required to excite the extra phases.

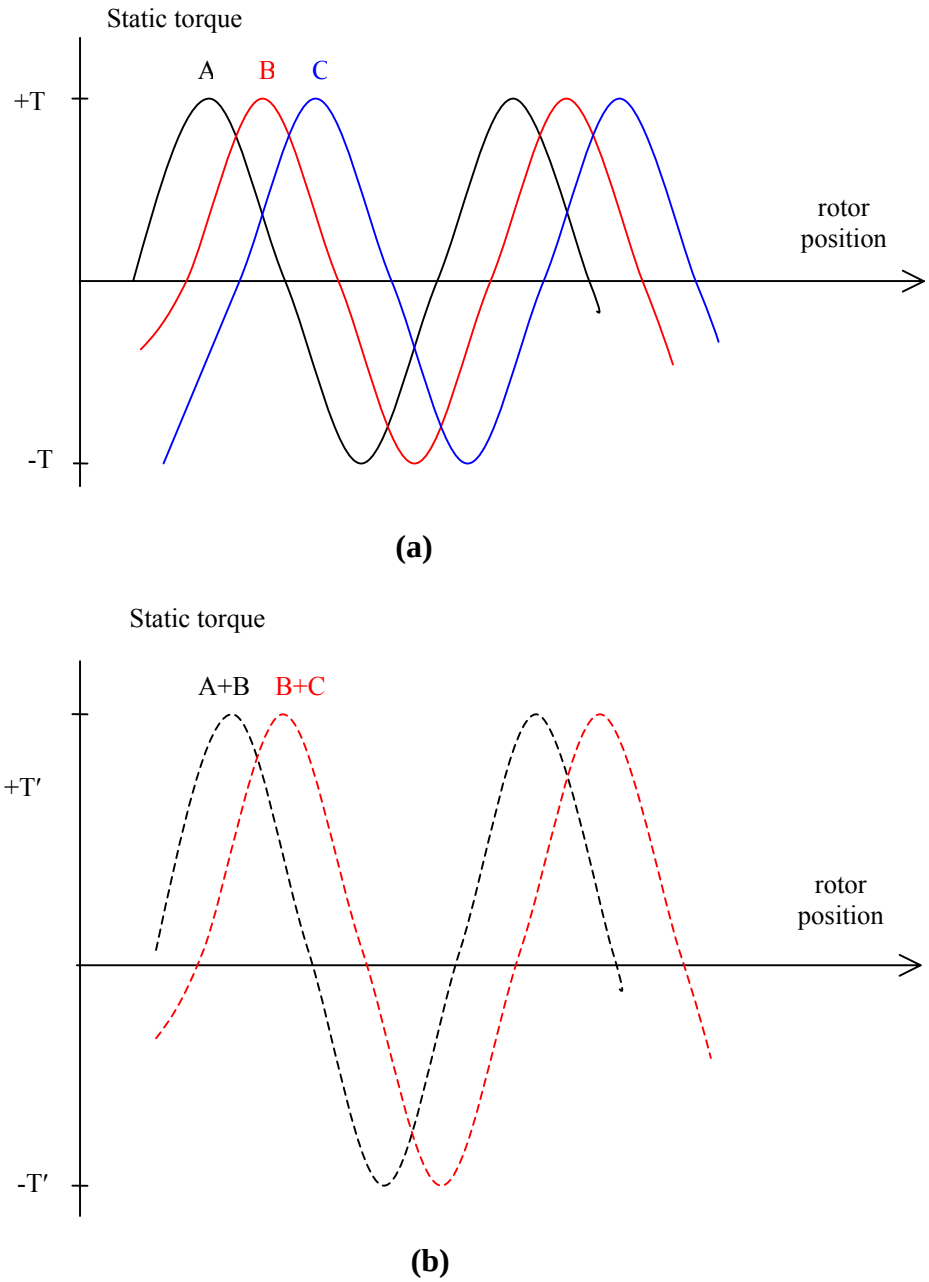


Figure 2.11 Static torque/rotor position characteristics for a variable reluctance stepping motor (a) one-phase-on excitation (b) two-phases-on excitation

2.6 Torque-Speed Characteristics

The torque-speed characteristics, that show the maximum torque which the motor can develop at each operating speed, are the key to selecting the right motor

and drive method for a specific application. These characteristics are dependent upon the motor, excitation mode and type of driver or drive method. A typical torque-speed characteristic of a stepping motor is given in Figure 2.12 in which there are pull-in and pull-out curves. The former defines an area referred to as the start stop region and this is the maximum frequency at which the motor can start/stop instantaneously, with a load applied, without loss of synchronism while the latter defines an area referred to as the slew region and it defines the maximum frequency at which the motor can operate without losing synchronism. Since this region is outside the pull-in area the motor must accelerated or decelerated into this region.

The pull-in characteristics vary also depending on the load as having the larger the load inertia the smaller the pull-in area. From the shape of the curve, it can be seen that the step rate affects the torque output capability of stepper motor. The decreasing torque output as the speed increases is caused by the fact that at high speeds the inductance of the motor is the dominant circuit element. The shape of the speed - torque curve can change quite dramatically depending on the type of driver used.

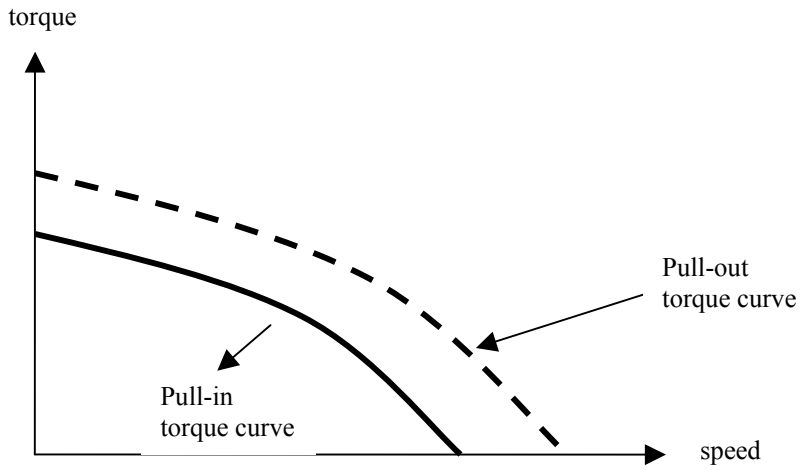


Figure 2.12 A typical torque-speed characteristics of a stepping motor

2.7 Step Motor Control

Step motors have an increasing application area and this is due to the wide selection of motor control systems that are currently available. The choice of a particular control scheme depends largely on whatever performance criteria and economic factors that has to be met in a specific application. Once an initial selection has been made among the types of the step motors, the next step is to determine the best combination of the motor and the control type.

Step motor control systems can be generally classified into two groups: the open-loop and closed-loop systems. In these basic categories there are several control variations, each of which has its own characteristics and applications. In general, any step control system can be represented by a simplified system as shown in Figure 2.13. In this system, the command source, where start-stop and direction commands are generated, may be a manual or local control or part of a controller in a larger system. The function generator is the source of step motor advance pulses which are manipulated in such a manner so as to achieve the desired motor dynamics. The sequence logic provides for proper driver switching sequences. The motor drive circuits consist of solid state devices capable of sufficient current carrying capacity and voltage breakdown protection to handle worst case operating conditions. If closed loop operation is desired then an optical, magnetic or capacitive feedback device is used in conjunction with an amplifier to supply feedback signals to the function generator.

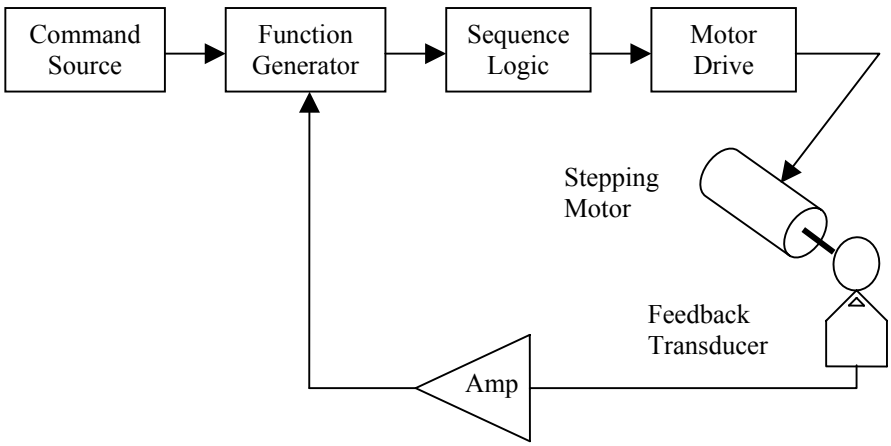


Figure 2.13 Simplified step motor control system

Stepping motors are often used as output devices for microprocessor-based control systems. The essential feature of these systems is that the microprocessor program produces a "result" and the stepping motor must then move the load to the position corresponding to this "result". Figure 2.14 shows an open-loop microprocessor controlled step motor where the phase control signals are calculated within the microprocessor according to the timing and sequencing requirements.

The second method is hardware-based system in which the microprocessor program feeds the target position information and a start controller which generates the phase control signals for the motor drive circuits and a finish signal for the microprocessor when the target is reached. In applications involving the real-time control of several other devices this method may be the only realistic alternative because of programming constraints.

2.7.1 Open-Loop Control

The open-loop control scheme has the advantages simplicity and low cost. A typical microprocessor-based open-loop control system is shown in Figure 2.14. as

seen in this figure, the digital phase control signals are generated by the microprocessor and amplified by the drive circuit before being applied to motor.

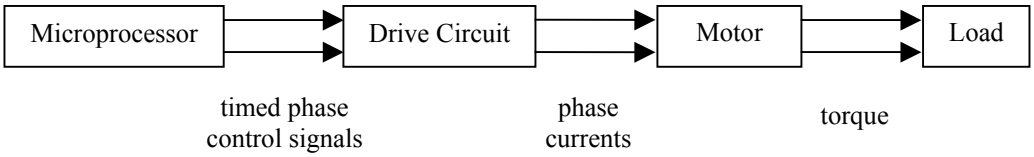


Figure 2.14 A typical microprocessor-based open-loop control

In an open-loop system there is no feedback of load position to the controller and therefore it is imperative that the motor responds correctly to each excitation change. If the excitation changes are made too quickly the motor is unable to move the load to the new demanded position and so there is a permanent error in the actual load position compared to the expected one. Also it is important that in the applications where the load is likely to fluctuate the timings must be set for the worst conditions, i.e. the largest load, and the control scheme is then non-optimal for all other loads. As there is no feedback in this type of control, the need for expensive sensing and feedback devices such as optical encoders is eliminated. The position data is simply get by keeping track of the input step pulses.

An open-loop control system of a step motor suffers from the disadvantage that the motor may not be able to follow the input pulse train so that the top speed which a motor can run is limited. Also, the speed of a step motor under open-loop control may have wide fluctuations. But it is still true to say that an open-loop system is entirely adequate for many applications.

2.7.2 Closed-Loop Control

A closed loop system can overcome the difficulties met in an open-loop control system by using positional feedback to the step motor to determine the proper

positions at which phase switchings should occur. With the closed loop control, one not only achieves much higher speeds and more stability in speed, but more versatility in many other aspects of the control of the step motor. Each step command is issued only when the motor has responded satisfactorily to the previous command and so there is no possibility of the motor losing synchronism.

A block diagram illustrating a closed-loop control scheme of a step motor is shown in Figure 2.15. The feedback sensor in this case could either be a photoelectric device or a magnetic pickup device which would give a pulse for every step of motion. The motor is started initially with one pulse from the controller and subsequent pulses are generated from the feedback sensor assembly. [3]

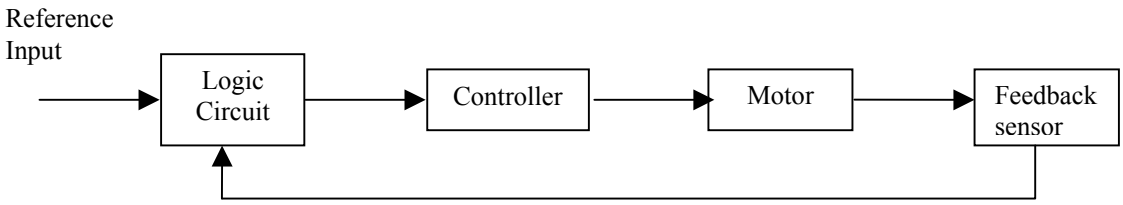


Figure 2.15 Block diagram of a closed-loop control of a stepping motor

CHAPTER 3

HARDWARE AND SOFTWARE SOLUTIONS

It is obvious that in order to obtain a drilling process from a digitally generated object will require hardware and properly designed software. As it is desired to have a precisely drilled object it is convenient to use step motors, as covered in the previous chapter, for this specific application.

The critical point in the software is that to convert the given image of the object in a way that the computer can send the data through the parallel port to the hardware of the system as digital control signals. The digital control signals for the step motor drive circuit are generated from the parallel port of the computer. As a control method, an open-loop control system (see 2.7.1) is used with only full step mode of operation (see 2.3). The mode of operation for all motors is always full step regardless of the direction of rotation of the motors that is clockwise or counter-clockwise.

3.1 Hardware

Hardware configuration consists of three stepping motors (X, Y and Z motors) that are responsible from the control of movements in the corresponding directions, driver cards for each motor, a XYZ positioning table and digital I/O for the control motors.

3.1.1 Digital I/O

3.1.1.1 Requirements for Digital I/O

Base drive circuit is designed such that the control signals are at TTL logic level which is 0 or 5 Volts. In order to have maximum efficiency in the system, these control signals must be as fast as possible. This speed depends on the torque requirement from the motor, simply the physical characteristics of the material drilled, and the control scheme of the motors. As stated in the previous chapter, closed-loop control scheme will require faster signals than the open-loop case. Experimental results show that with the open-loop control scheme, motor types and material given, 5 msec, as the step motor pulse duration is adequate.

These signals may be generated by specially designed, commercially available professional devices that are sold by various vendors with respectively higher prices. Another solution for digital I/O is utilizing the parallel port which is available on every personal computer.

3.1.1.2 Parallel Port of PC

Parallel port is a standard I/O interface for all PCs. Today, there exists at least one parallel port for various applications such as connection of a printer or a hard-key. In Table 3.1, the base hardware addresses of the parallel ports are given.

Table 3.1 Parallel Port Address Table

Name of the Port	Data Port	Status	Control
LPT1	378h	379h	37Ah
LPT2	278h	279h	27Ah
LPT3	3BCh	3BDh	3BEh

There exist three types of I/O interface in the parallel port namely data port, status port and control port.

- Data Port : There exist eight digital output terminals that are accessed by data ports.
- Status Port : There exist five digital input terminals, of which one of them is inverted, that are accessed by status ports.
- Control Port : There exist four digital output terminals, of which three of them are inverted, that are accessed by control ports.

All ports are defined at TTL logic levels (An electrical "high" on the pin is TTL high, +2.4 to +5 volts. An electrical "low" is TTL low, 0 to +0.8 volts.). Data port is driven by the high impedance octal D-type flip-flop (74LS374). This IC can source 2.6 mA while it can sink 24 mA. As these values are relatively low, it may be necessary to amplify the outputs for specific applications. Control port pins are driven by the 7405 inverter IC which may supply 1 mA up to 7 mA. In parallel port applications, for not to damage the mainboard the driver circuits should fulfill the requirements given above.

In Figure 3.1, the block diagram of the parallel interface is given while in Figure 3.2 the illustration of a parallel port is shown.

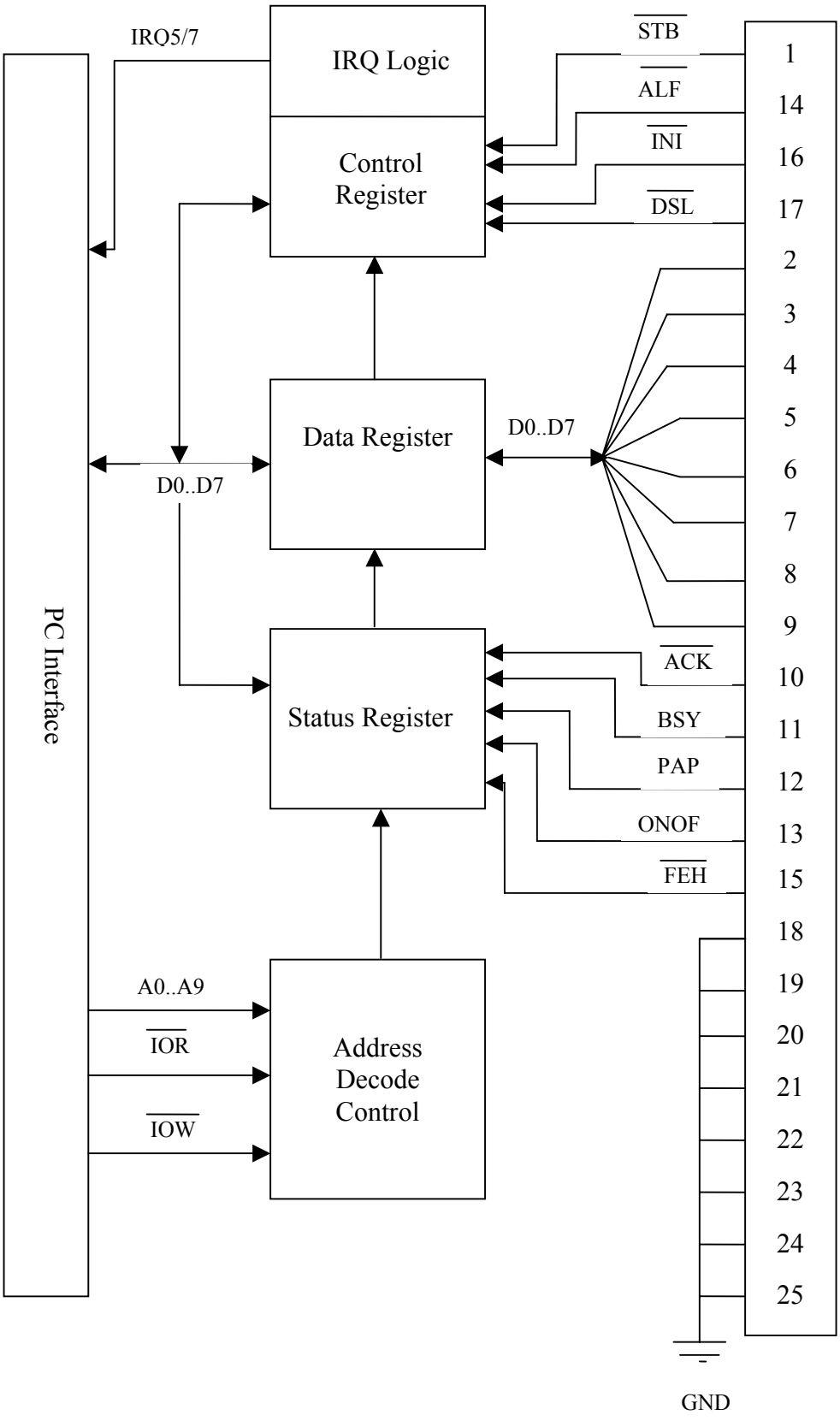


Figure 3.1 Block diagram of the parallel interface

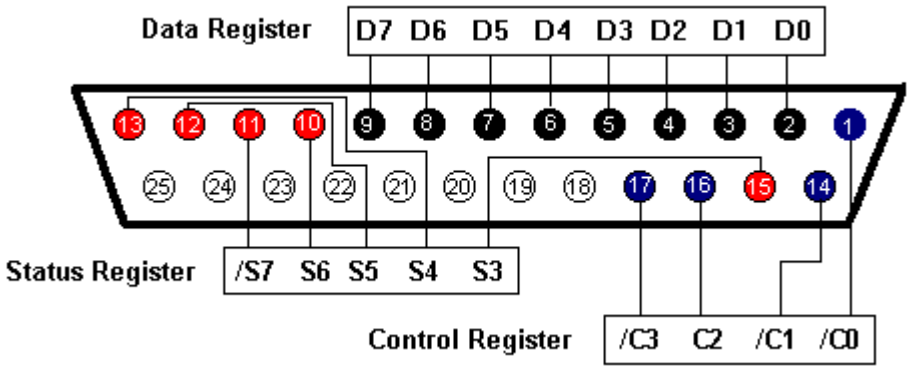


Figure 3.2 Parallel Port I/O Scheme

3.1.2 Stepper Motor Driver Circuit

The drive circuits are used to drive the two phase bipolar X, Y and Z step motors. The drive circuit to drive the X and Y axes is given in Figure 3.3 while the circuit for driving the Z axis is given in Figure 3.4. The principal function of the driver circuits is to generate motor phase sequences.

In these circuits L298 dual full-bridge driver and L297 stepper motor controller IC (see Appendix C) are used as motor drive circuit components. There are three control signals, which are used to control the each of the motor axes, as “clock” to give the stepping command, “direction” to determine the sense of rotation of the motor and “half/full” to decide whether to operate in full or in half step mode. Although it is possible to choose full or half step mode, only the full step mode is used as it is indicated before. Normal drive mode is practiced to for the full step mode and it is selected by a low logic level on Half/Full* input (Full step mode). In this mode Inh1* and Inh2* outputs remain high throughout the operation [4].

The cable connection used between the stepper motor controller circuit inputs to the proper outputs in order to drive the step motors are given in Table 3.2, Table 3.3 and Table 3.4.

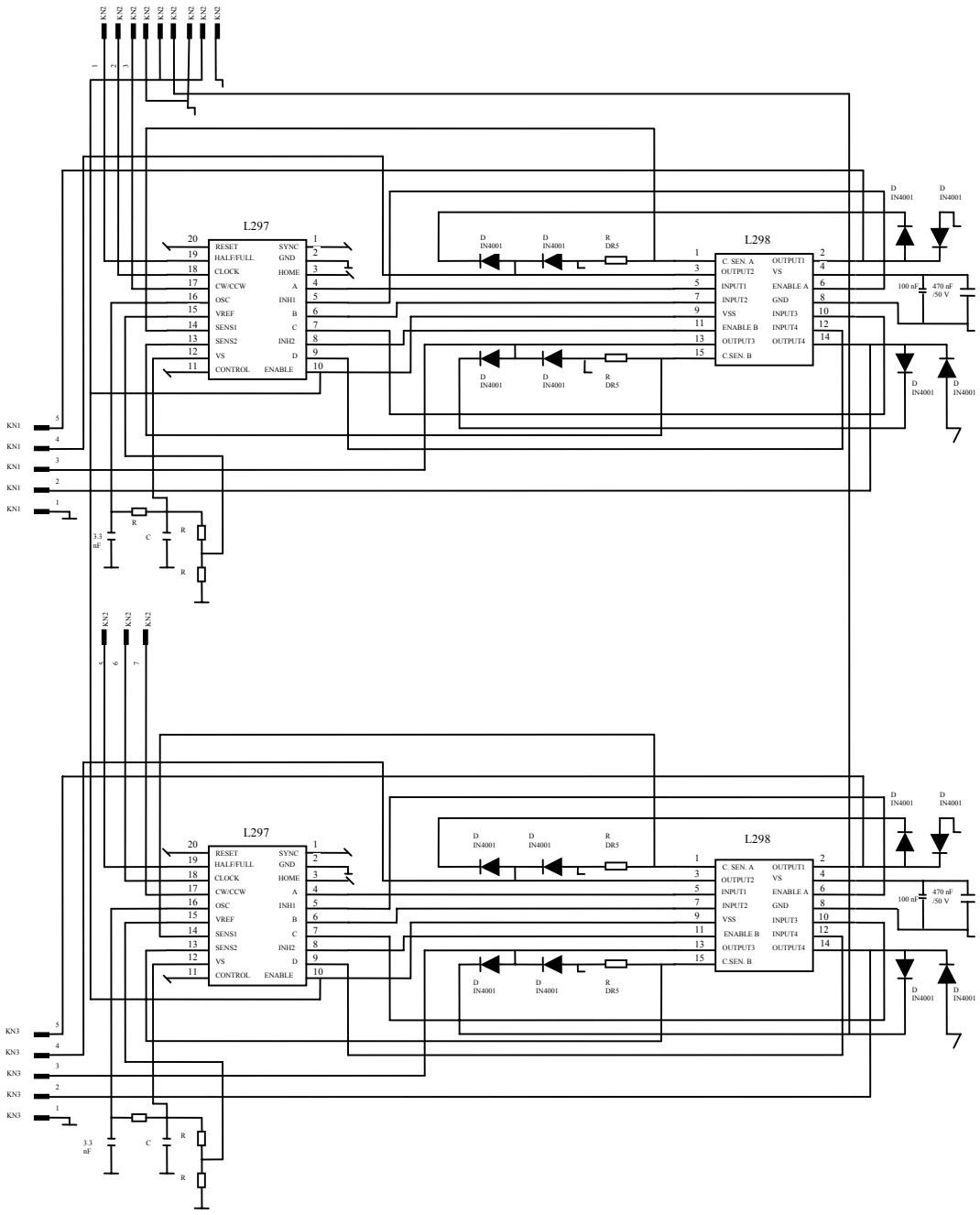


Figure 3.3 (X-Y) Axis Drive Circuit

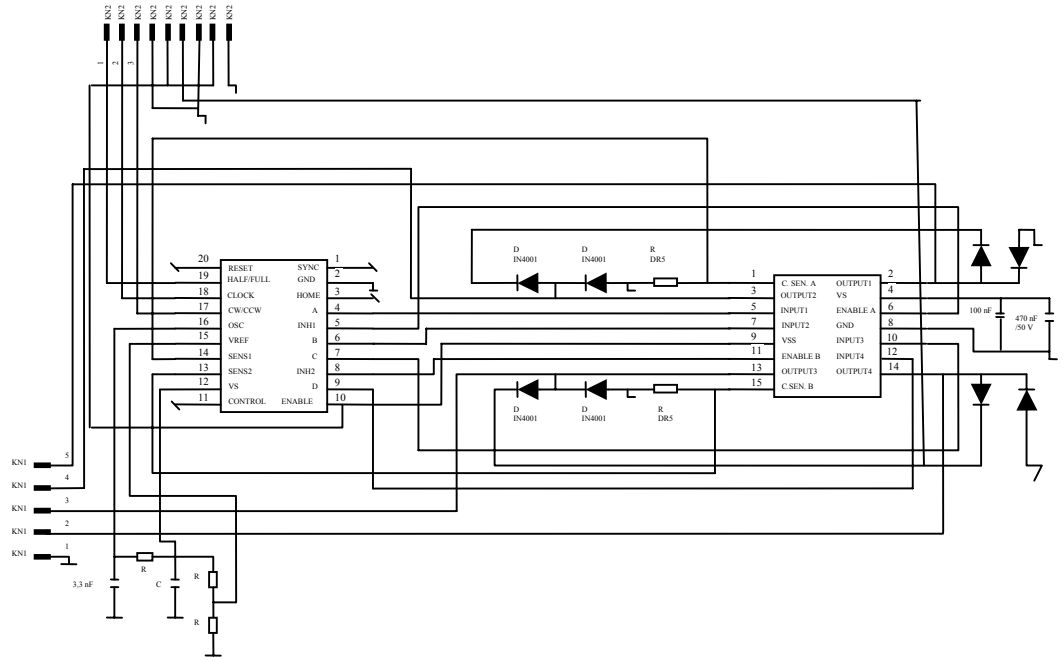


Figure 3.4 Z Axis Drive Circuit

Table 3.2 Cable connection of X-Y axis card

X-Y Axis Card	Parallel Port Connector	Stepper Motor
KN1-1	-	GND pin of Y axis motor
KN1-2	-	Phase line 1 of Y axis motor
KN1-3	-	Phase line 2 of Y axis motor
KN1-4	-	Phase line 3 of Y axis motor
KN1-5	-	Phase line 4 of Y axis motor
KN3-1	-	GND pin of X axis motor
KN3-2	-	Phase line 1 of X axis motor
KN3-3	-	Phase line 2 of X axis motor
KN3-4	-	Phase line 3 of X axis motor
KN3-5	-	Phase line 4 of X axis motor
KN2-1	Pin 1 (Half/Full*)	-
KN2-2	Pin 6 (Clock X)	-
KN2-3	Pin 7 (Cw/CCw X)	-
KN2-5	Pin 1 (Half/Full*)	-
KN2-6	Pin 4 (Clock Y)	-
KN2-7	Pin 5 (Cw/CCw Y)	-

Table 3.3 Cable connection of Z axis card

Z Axis Card	Parallel Port Connector	Stepper Motor
KN1-1	-	GND pin of Z axis motor
KN1-2	-	Phase line 1 of Z axis motor
KN1-3	-	Phase line 2 of Z axis motor
KN1-4	-	Phase line 3 of Z axis motor
KN1-5	-	Phase line 4 of Z axis motor
KN2-1	Pin 1 (Half/Full*)	-
KN2-2	Pin 2 (Clock Z)	-
KN2-3	Pin 3 (Cw/CCw Z)	-

Table 3.4 Cable connection of cards and supply

X-Y Axis Card	Z Axis Card	Power Supply	Cable Connector
KN2-8	KN2-8	+5V	-
KN2-4	KN2-4	GND	GND pin1
KN2-9	KN2-9	+24V	-

3.1.3 Stepper Motors

The stepping motors are used to drive the positioning table in X and Y directions and the cutter in Z direction. The motors used are two phase bipolar stepping motors with 1.8 degrees per step. The rated voltage for one of them is 5 V DC and 3.2 V DC for the other two. In case of using motors with different degrees per step, the constant values in the equations (4.1) and (4.2) must be changed due to the motor type selection.

3.1.4 Drilling Material and Cutting Tools

For different types of applications there exist various kinds of drilling materials and consequently there are proper cutting tools for every drilling material. The drilling materials can be classified basically as follows.

- Soft Materials (perspex, fiber, etc.)
- Soft Metals (brass, aluminum, etc.)
- Materials made of steel

As a cutting tool, the HSS (High Speed Steel) is used for the first two types while tungsten-carbide type is preferred for the materials that are made of steel. The tip type must also be considered according to the object to be drilled. For example, it is proper to use a cornered tip for a rectangular shape, while a round tip is more convenient for an elliptical one.

3.2 Software

The software should be developed under a GUI based programming language, which is a more powerful language compared to the other ones, following the reasons given in 3.2.1.

The software consists of three main modules (Figure 3.5) which are image processing software module that handles the digitizing issues of the image, step motor control software module that is associated with the drilling process and finally the parallel port control software module that is, in fact can be thought as a submodule of the step motor control software module, responsible for the communication between the hardware part and the software.

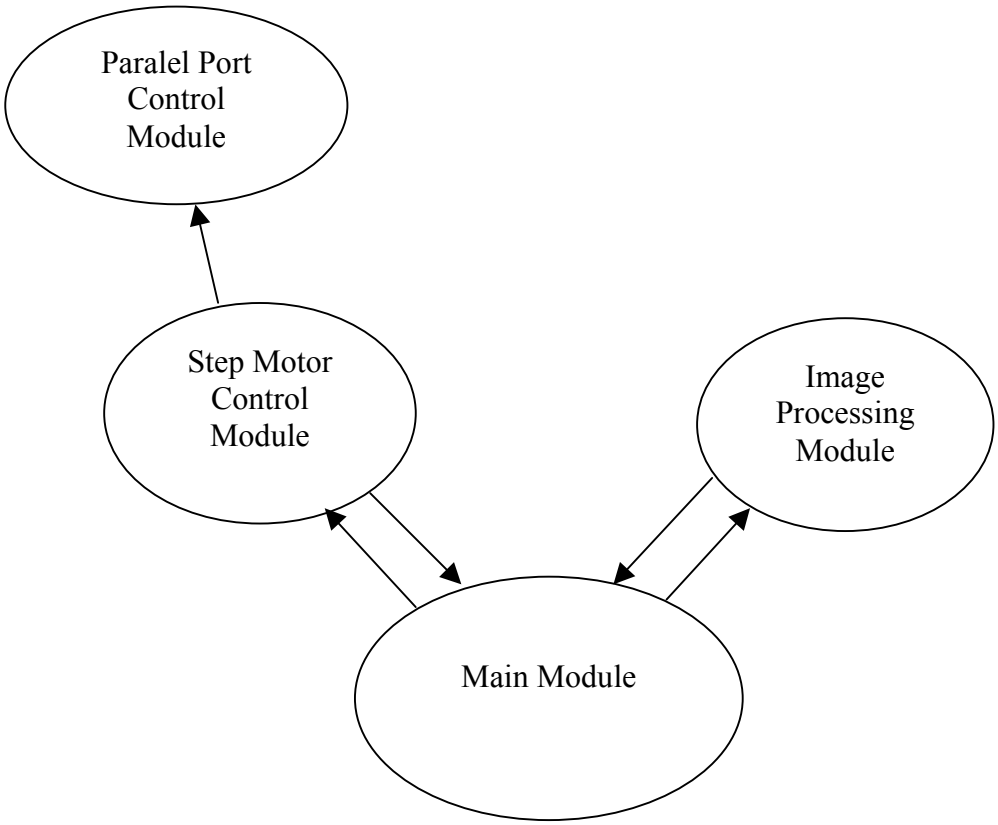


Figure 3.5 Software Modules Data Flow Diagram

3.2.1 GUI Based Programming Languages

GUI based languages, such as Visual Basic and Visual C, are today's state-of-the-art programming languages that are respectively powerful than the former programming tools. They ease the burden of programming with more user friendly graphical interfaces. In Table 3.5, the lines of code per complexity unit are given for different programming languages [7].

Among various GUI based languages, Visual Basic is the most user-friendly and easy to use respectively. Because of these properties, Microsoft Visual Basic 6.0 is used in this thesis.

Table 3.5 A rough estimation of average number of LOC required for building one complexity unit in various programming languages.

Programming Language	LOC/Complexity Unit
Assembly language	320
C	128
Cobol	105
Fortran	105
Pascal	90
Ada	70
Object-oriented languages	30
Grapchical languages	4

3.2.2 Step Motor Control Software

One of the critical points in the software is to send the data to the driver circuit properly i.e. to the right axis with the right timing. The main module sends how many pixels to move in which direction.

The first step is to determine the movement axes that are in fact to determine to change which bits of the parallel port. Then the number of steps should be extracted from the multiplication of the step/pixel and the pixel count. A counter variable is utilized to keep the track of the steps achieved where the value of is initialized to zero. According to the axes and movement determined the signals are generated and sent to the driver circuit. Note that there should be a delay between the two steps of the motors because of the reasons discussed in Section 2.6. The usage of the open-loop control simplifies the process as there is no feedback. In Figure 3.6 the flowchart of the step motor control software is illustrated.

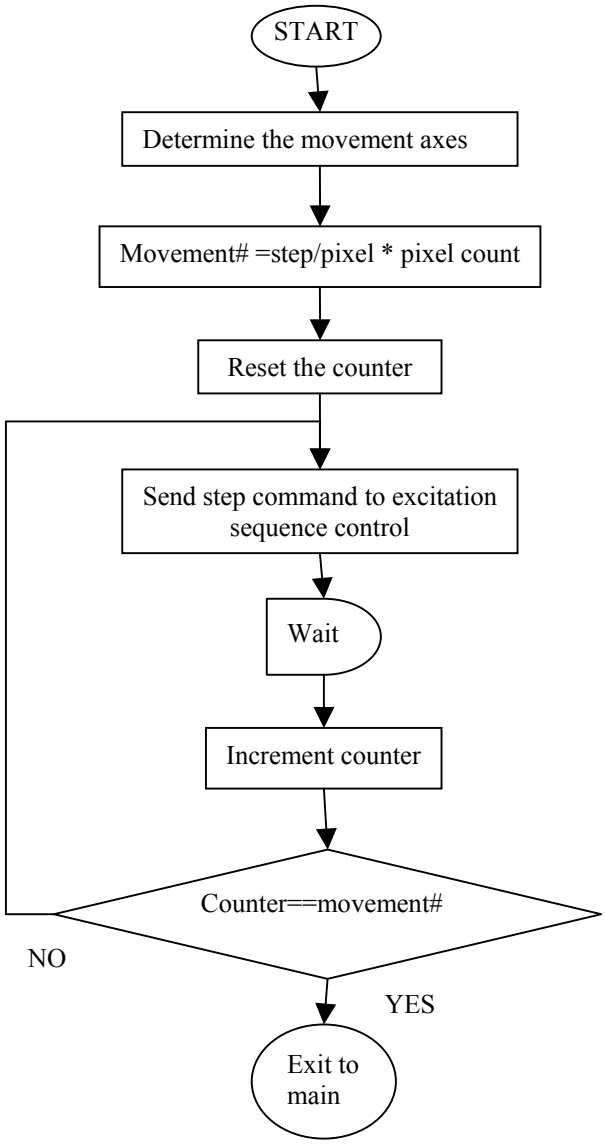


Figure 3.6 Flow Chart of the Step Motor Control Software

3.2.3 Parallel Port Control Software

Microsoft Visual Basic could access the parallel port of the computer without introducing an additional interface program (these programs are called drivers) in Windows 9X OS. By using "c:\windows\system\win95io.dll" library file it is possible to access the parallel port of the computer [5]. Because of the "Hardware Abstraction Layer" of Windows NT and Windows 2000, none of the applications can directly access to the hardware, ports and devices. The remedy for this problem is to

introduce a third party program. One of these third party programs that can be easily obtained and can be used is the “I/O ActiveX Communications Control Software” (Figure 3.7) [6]. Application of this program will provide the developed software to run independent from the type of the windows OS.

The I/O ActiveX Communications Control Software is an ActiveX control software component that can easily be used in a variety of “Visual” programming environments. To use an ActiveX control, it must first be installed on the system being used for development. Then it can be inserted into the programming environment where it will be used. ActiveX controls are typically inserted on a form. After the control is placed on the form the member functions and properties are available to be used by the programmer.

Figure 3.7 I/O ActiveX Communications Software Message Box

3.2.4 Image Processing Software

The modules and the critical methods used while developing the modules are explained in Chapter 4 in detail. The critical algorithm of the software is built by the connectivity and contour tracing issues.

3.2.4.1 Definitions of Connectivity and Contour Tracing

In a discrete binary image, objects are represented in terms of discrete pixels. A square tessellation is a partitioning of a plane into regions of square parts and a regular tessellation means a tessellation made up of regular polygons that are same size and shape [8]. In Figure 3.8, a black pixel p and the neighborhood of p, that is

the set of pixels intersecting p, are shown. The eight neighbors of p can be classified into two groups as having an edge in common with p or having a point in common with p. The former, which is shown with shaded areas in Figure 3.8, is called the "4-neighbors" of p while the latter, that is the whole neighbors of p, is called "8-neighbors" of p.

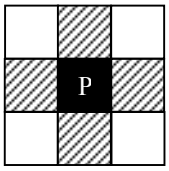


Figure 3.8 Neighbors of a pixel p in a square tessellation

An object or pattern in a tessellation is said to be a connected component of black pixels where the background is assumed to be consisted of white pixels or vice versa. As having two types of neighbors, there are two types of connectivity as "4-connected" and "8-connected". In other words, if the neighbors of a pixel, in an object or pattern, are only of type "4-neighbors" then it is said to be a "4-connectivity", otherwise "8-connectivity". In Figure 3.9 examples of 4- and 8-connectivity are shown. Following the connectivity definitions, *Jordan Curve Theorem* says a simple closed curve separates the plane into two simply connected components (namely, the inside and the outside) [9, 10]

(a) (b)

Figure 3.9 Examples of (a) 4-connectivity (b) 8-connectivity

3.2.4.2 Pseudo Code of Contour Tracing

For the contour tracing of a point with 4-connectivity, whose neighbor tracking sequence is given in Figure 3.10, the following algorithm is used. Note that the final value for counter I in this code would be converted to eight in case of the application of an 8-connected point.

The pseudo code for the algorithm:

```
Repeat until no black_neighbor found
    For I=1 to 4
        If neighbor(I)=black then
            Assign this point to next examination point
            Save this point
            Break
        Else
            Continue
        End If
    Next I
Loop Repeat
```

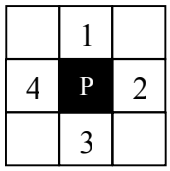


Figure 3.10 The tracking sequence of neighbors for 4-connectivity

CHAPTER 4

SOFTWARE DESCRIPTION

4.1 Software Requirements Specifications

- Software should be able to load, digitize and drill the 2D and 3D images which are properly designed and drawn as given in 4.1.1.

- The program should let the user to choose the following options to be chosen from the start up screen.
    - Show/Do not Show “Current Position” of the motors in “mm” units.
    - Show/Do not Show “Current Position” of the motors in “pixel” units.
    - Enable/Disable “Pause Program”.
    - Draw/Do not Draw the track of the motor movement.

- The main screen of the program should show the following information.
    - A user information message area.
    - Elapsed and remaining time information during the drilling process.
    - The name and the path of the selected image file.
    - The required options that are selected from the start up screen.
    - A “Stop” button to stop the drilling.
    - A “Start At (X, Y, Z)” button to start the drilling at a specified (X, Y, Z) point.
    - A “Pause” button to pause the drilling process.

- A ”Pause Program” button to program the position of the pause action.
- A “GoTo (X, Y, Z)” button to make the motors to go to a specified point.
- A menu consisting of “File”, “Digitizing”, “Drilling”, “3D Menu”, “About” and “Exit”.
- The menu items are going to be enabled in a logical way. For example the “Digitizing” item is going to be enabled only after the file to be loaded is selected.
- The “File” item should consist of “Load Image File”, “Load Digitized Image” and “Save Digitized Image”.
- The “Digitizing” item should consist of “Digitize Min Distance” and “Digitize Top”.
- The “Drilling” item should consist of “Drill Image”, “Drill Options” and “repeat Drill”.
- The “3D Menu” item should consist of “3D Imaging”.

- After the selection of the image file from the “Load Image File” item under the “File” item of the menu, the “Digitizing “ item should be enabled.

- After the digitizing process, that begins with the selection of either “Digitize Min Distance” or “Digitizing Top”, an “Image Property Window” showing the following information should appear.
  - Maximum dimensions of the object that would be drilled in pixel and mm. units.
  - Number of images found.
  - A warning for checking the image file if the number of images found is not the expected one.

- After closing the “Image Property Window” the “Drilling Options” window should open having the following properties.

- A textbox to enter the pulse delay value of X and Y motors and a textbox to enter the pulse delay value of Z motor in milliseconds.
- A textbox to enter the step per pixel value of X and Y motors and a textbox to enter the step per pixel value of Z.
- The possibility of choosing “Delta Z Profile” to use a z-axis profile file, “Delta Z Uniform” to use a uniform depth or “Delta Z” to give different depth levels (up to 20 levels at most depending on the number of images) manually.
- A “Defaults” button to have the default values instead of entering them manually.

- A “Job Finished” message box also showing the total time elapsed for drilling.

- General requirement for the program:
  - All errors will be handled by the error handling procedures.

4.1.1 Image Requirements and Limitations

For the drawing of a two dimensional object, that means in fact a three dimensional object is got from the drawing of top view and proper depth value(s), the following requirements and limitations should be covered.

- The background should be white where the drawing is black in color. A typical drawing for a two dimensional object is shown in Figure 4.1

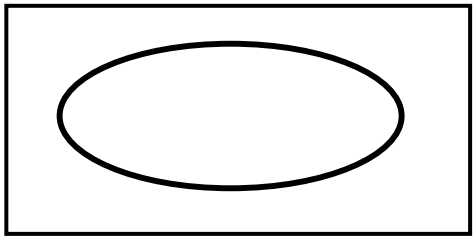


Figure 4.1 A typical drawing for a two dimensional object

- There should not be any points on the neighborhood of the peripherals.

False True

Figure 4.2 The requirements and limitations concerned with the peripherals

- There should not be more than two neighbors of a point.

Figure 4.3 The requirements and limitations concerned with the number of neighbors of a point

For the drawing of a three dimensional object, that means a three dimensional object is got from the drawing of top view, whose inside region is red, and proper profile, the following requirements and limitations should be held.

- The background should be white where the drawing is black and the inside part of the drawing is red in color. A typical drawing for a two dimensional object is shown in Figure 4.4.

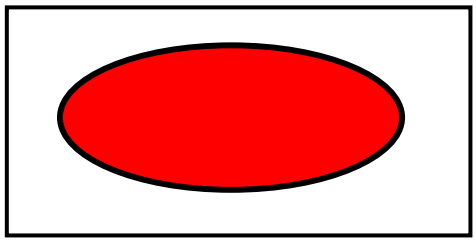


Figure 4.4 A typical drawing for a three dimensional object

- The contour of the drawing, i.e. the black part, must be closed.

- There should not be any contour, i.e. black points, on the neighborhood of the peripherals and there should not be more than two neighbors of a black point as it is in the requirements and limitations of the drawing of a two dimensional object.

The drawing of a profile to be used as the depth function of 3D images the following requirements should be covered.

- The horizontal axis should be the axis for the layers of the object and the vertical one for the depth values of the layers in the z-direction.

- There should not be any points on the neighborhood of the peripherals and there should not be more than two neighbors of a point.

- There should be only one z depth value for a given layer.

- The origin (0, 0) point should be in red color where the background in white, the axes in black and the function in blue color. A typical drawing for a two dimensional object is shown in Figure 4.5.

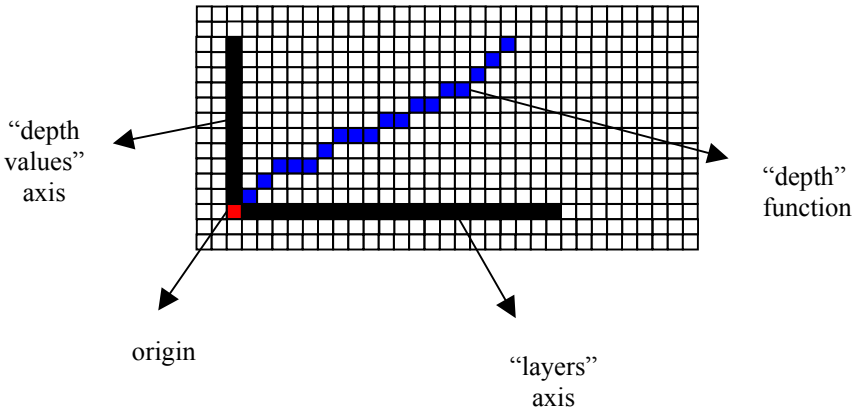


Figure 4.5 A typical drawing for a profile

4.2 Software Modules

Each of the modules of the program consists of the forms in Visual Basic. The modules are illustrated in Figure 4.6. As it is seen from the figure, the software consists of a main module which is responsible from all of the abilities of the system. Note that this figure does not show the sequence but the data flow between the modules.

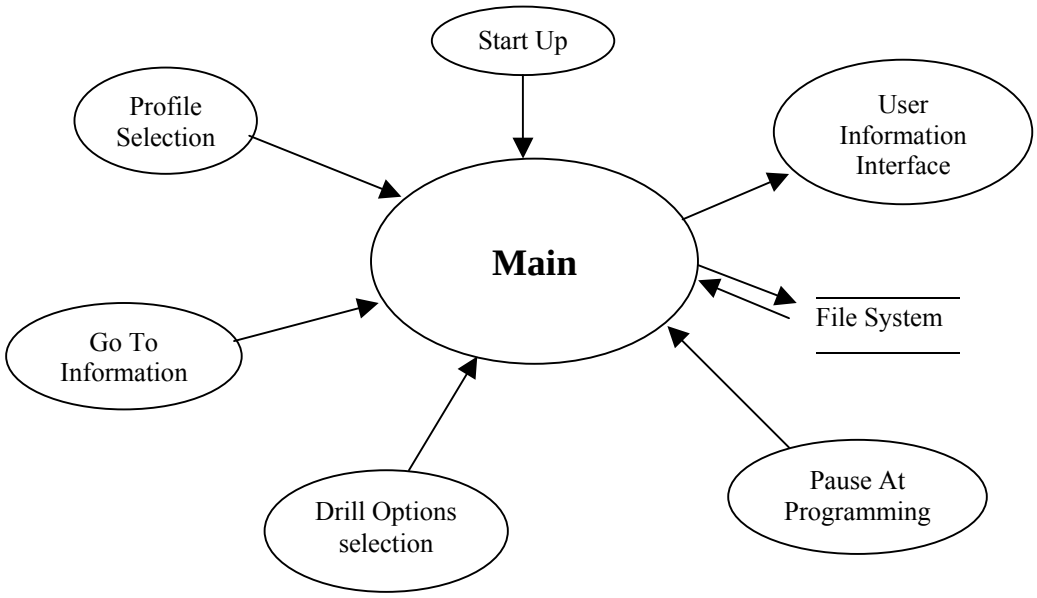


Figure 4.6 Software Data Flow Diagram

4.2.1 "Start Up" Module

As the name implies, the "Start Up" module is the first user interface seen when the program starts. Identity of the program and the programmer with the options are shown on this form. As seen in Figure 4.7, the following options, that would be used as the program is running, are available.

- The current position information (in pixel or millimeter units) that would appear in the main module to show the position of the cutter as the object is being drilled,

- The pause program option to be able to pause the drilling action and start again from the same position whenever wanted as the drilling of the object is going on.

- The drill tracking option that would show the track of drilling with a different color as the drilling of the object.

Although all these options useful in use, as they cause about a 10% increase in drilling time it is convenient not to select them when drilling time is important.

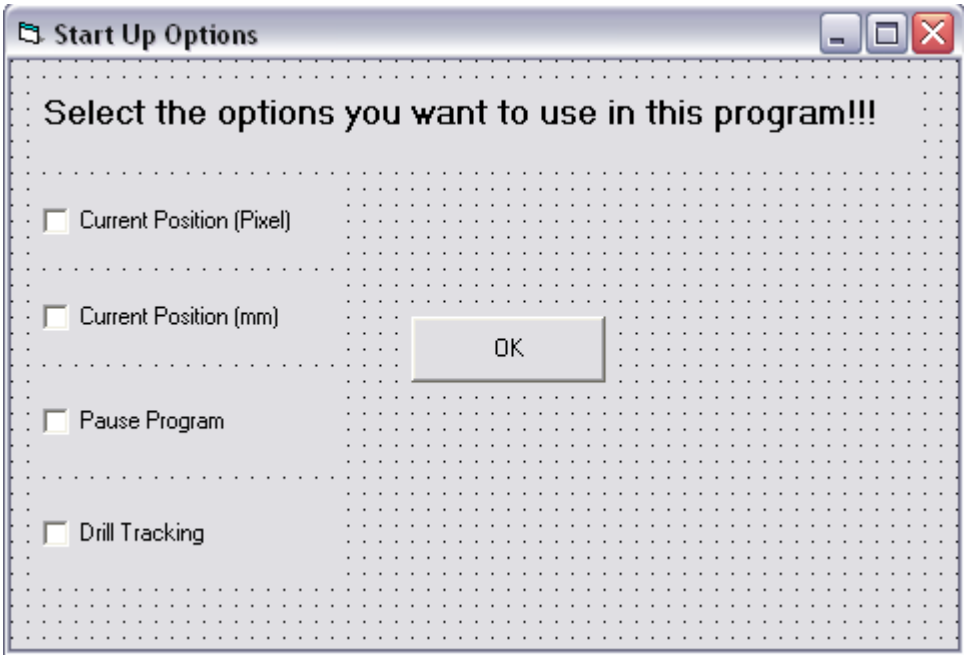


Figure 4.7 Start Up Module User Interface

4.2.2 "User Information Interface" Module

The "User Information Interface" module is called after an image digitizing process of the main module. On this form, the requirement of showing the physical properties, i.e. the dimensions, of the object is satisfied. With this property the user can know the exact size of the drilling material block that will be used for the desired object. Also the number of the images detected and a warning message against some mistakes that may be caused by the drawings out of standards are displayed. For example, if there is an extra point that does not belong to the object in fact, the program will take it as an object and the number of images counted by the program will be one more than the actual one. In such a case the user can control the drawing again to prevent a mistake.

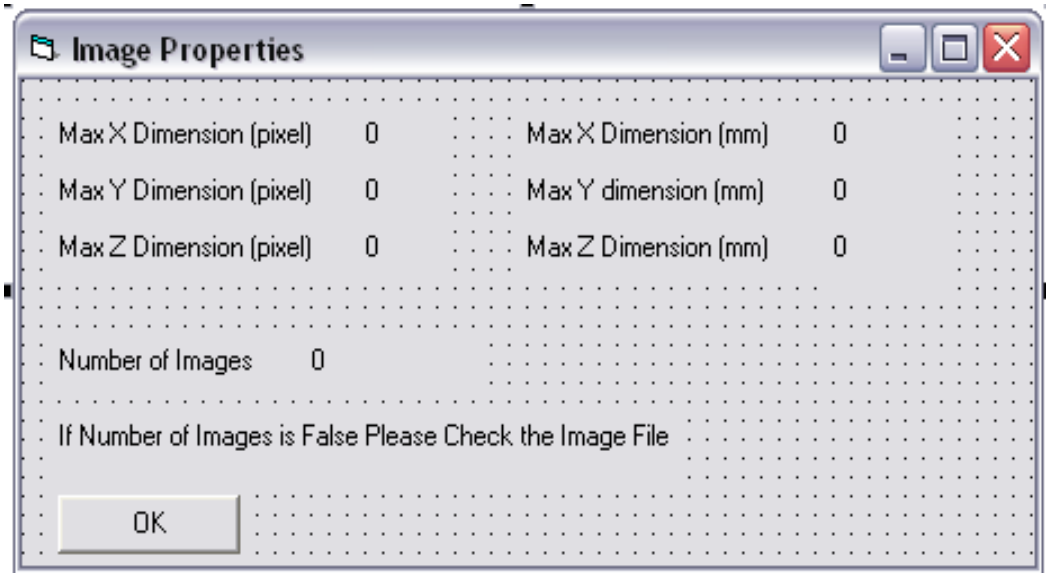


Figure 4.8 User Information Interface

4.2.3 "Drill Options" Module

The "Drill Options" module that is used for specifying motor actions and depth levels of the layers for the object to be drilled is called after "User Information Interface" module. In this module there are three options to specify the depth levels as "Delta Z Profile" accessing a z-axis profile file (see Section 4.1.1), "Delta Z Uniform" using a uniform depth level for all layers and "Delta Z" giving different depth levels. There are at most twenty different levels that can be specified manually. The number of those boxes, used to specify different depth levels, change in respect of the number of the objects detected. For example if there object are detected in the digitizing process, there will be three delta depth value boxes. The pulse delay values that are necessary for proper motor actions are also set on this form. As "diagonal movement", that is to move x and y motors simultaneously, is used the pulse delay values for these should be same. The number of steps for each motor per pixel is also set on this form. As it is seen in Figure 4.9 there is a "Default" button for using the default values that are the optimal ones for the motors specified. "Drill Options" module can also be used to change the options by the menu item "Drilling Options" under "Drilling".

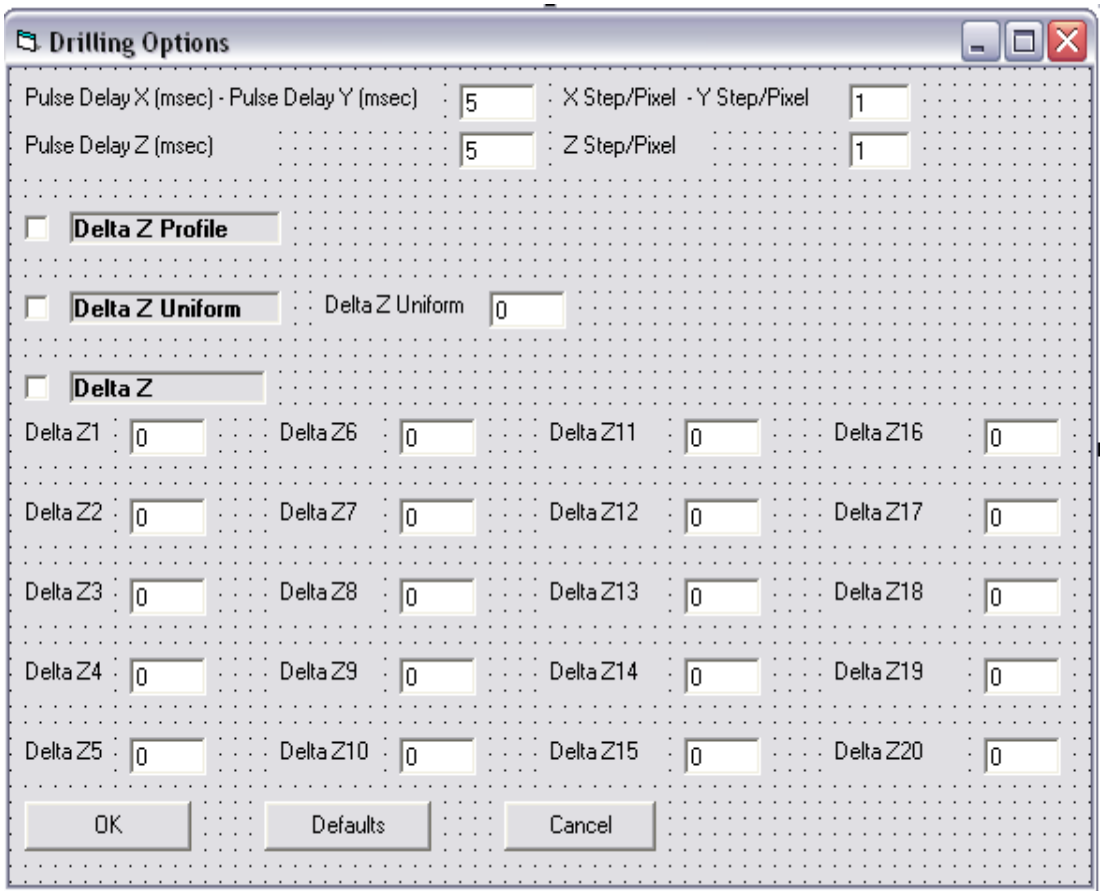


Figure 4.9 Drill Options Interface

4.1.1.1 Calculation of the Prototype Dimensions

In the prototyping process of an object, it is important to use the appropriate values in the "Drilling Options" to get the desired prototype with the desired size. As it is given in the equations (4.1) and (4.2), the actual size of the prototype is directly proportional with the number of pixels and step per pixel value for the relative direction and a constant.

$$d_{PHYSICAL\,X/Y\,(mm)} = n_{(pixel)} * (step/pixel)_{(X/Y)} * 0.0289 \quad (4.1)$$

$$d_{PHYSICAL\,Z\,(mm)} = n_{(pixel)} * (step/pixel)_{(Z)} * 0.0157 \quad (4.2)$$

4.1.2 “Go To Information” Module

The “Go To Information” module that is used to specify the position information of the actions “Go To”, “Start At” and “Pause At” is called with the relevant buttons on the main form. For “Go To” that is called to move the motors to the desired position there are also buttons to move them pixel by pixel. The movements are in terms of entered pixel value times the step per pixel value that is specified in the “Drilling Options” form. With “Pause At” it is possible to program the pause position before starting drilling but he position information that should be given in pixels has to match to a point on the drawing of the object otherwise it will not have any effect. There are also buttons on this form to move the motors to the desired position.

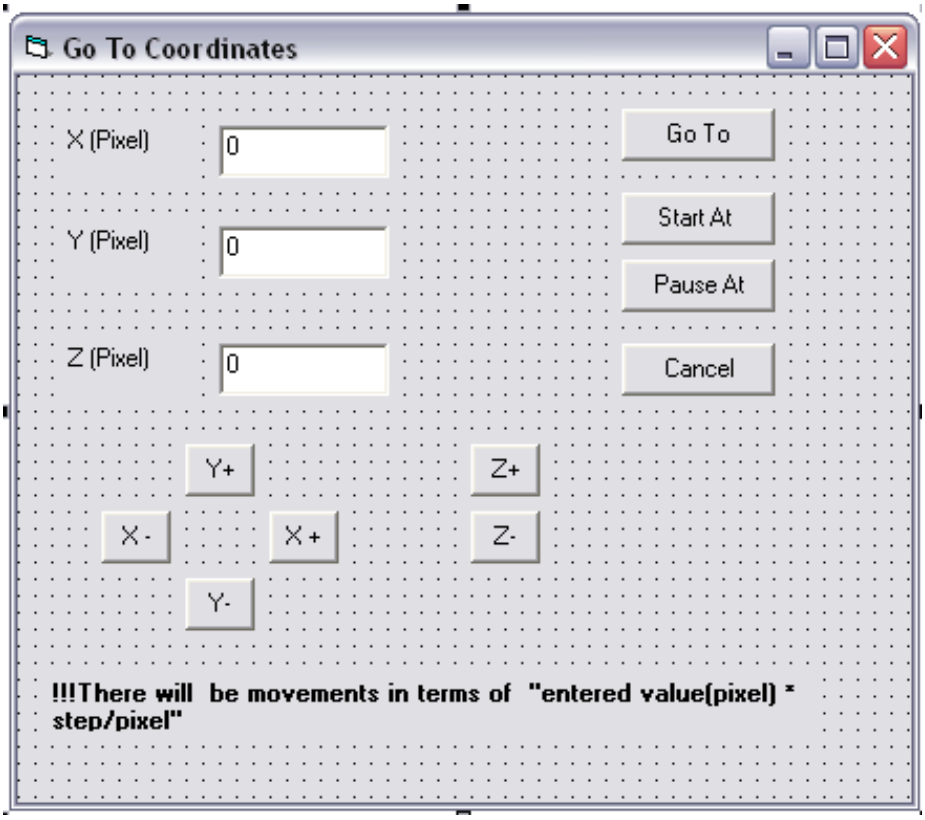


Figure 4.10 Go To Information Interface

4.1.3 “Profile Selection” Module

The “Profile Selection” module is called when the “Delta Z Profile” option in the “Drilling Options” form is selected. With the use of this module the drawing of a profile file, whose requirements given in Section 4.1.1, is called to be used as the depth function of three dimensional images. The critical point in loading a profile file is that the number of layers in the profile should be equal or greater than the number of layers that are found in the digitizing process of the three dimensional object, otherwise there will be an error message indicating this situation.

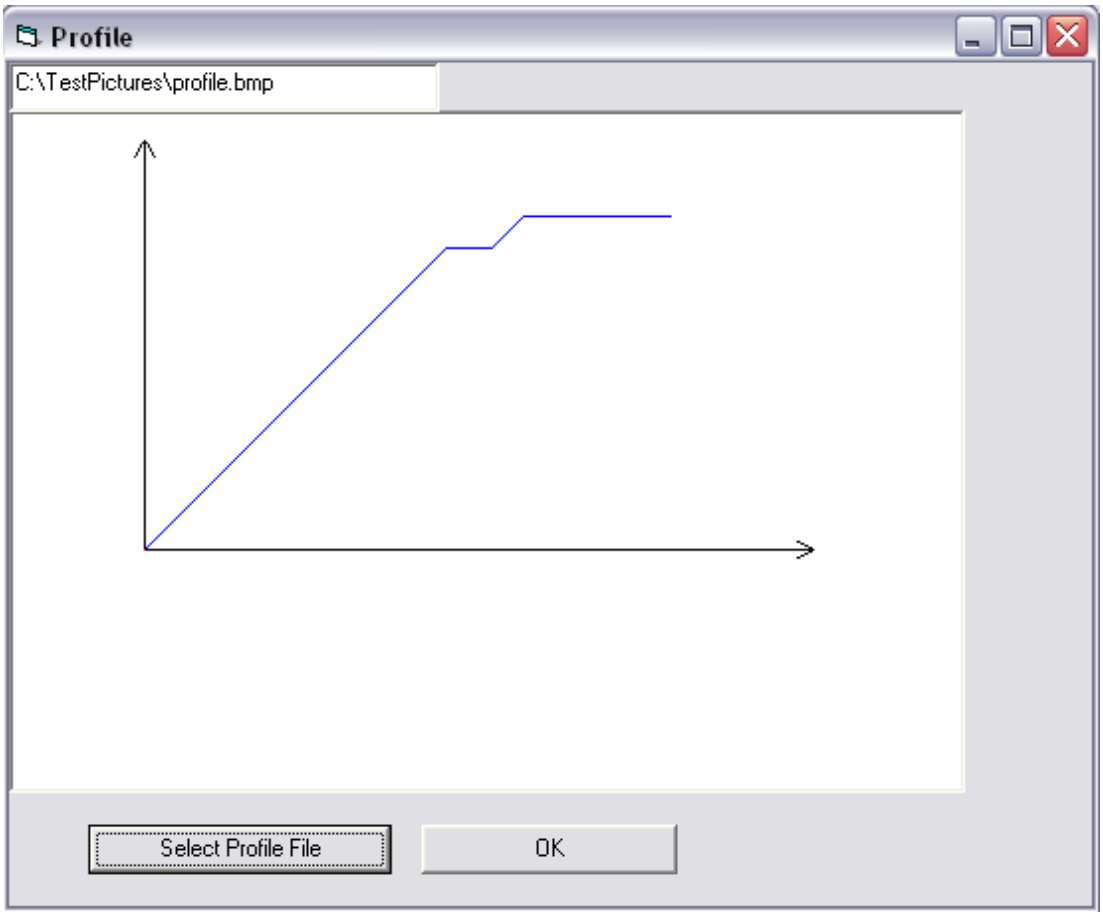


Figure 4.11 Profile Selection Interface

4.1.4 "Main" Module

The main module interface is shown in Figure 4.12 where the main drilling machine program controls take place. In this interface there are menu items as file, digitizing, drilling, 3D menu, about and exit with their sub-items and for the most common used ones shortcuts on the toolbar. There exist also two textboxes, one to show the file name and its path that is being digitized or drilled and one to give messages to the user for the next step to run the program properly.

The loaded object comes into sight on the "picture box" which changes its size automatically up to the size of the picture loaded. During the drilling process, the progress bar showing the percentage of the completed part, the time elapsed, current positions both in pixels and millimeters depending upon the choice made at the beginning of the program (see 4.2.1) are activated.

The "Start At (X, Y, Z)", "Go To (X, Y, Z)" and "Pause Program" buttons are used for the relevant actions (see 4.1.2). When the "Pause" button is clicked the program pauses regardless of the position of the cutter until it is re-clicked. With the "Stop" button it is possible to stop the process that is going on and start the process for a new object without exiting the program.

As the "Debug Mode" is enabled by clicking its checkbox, the drilling process is carried without sending any signals to the parallel port, i.e. it does not drill in fact but the drilling process can be observed on the screen as if it is drilling. It is obvious that a this kind of process takes much shorter time than drilling the object with the cutting tool so it is sometimes better to use this property before drilling.

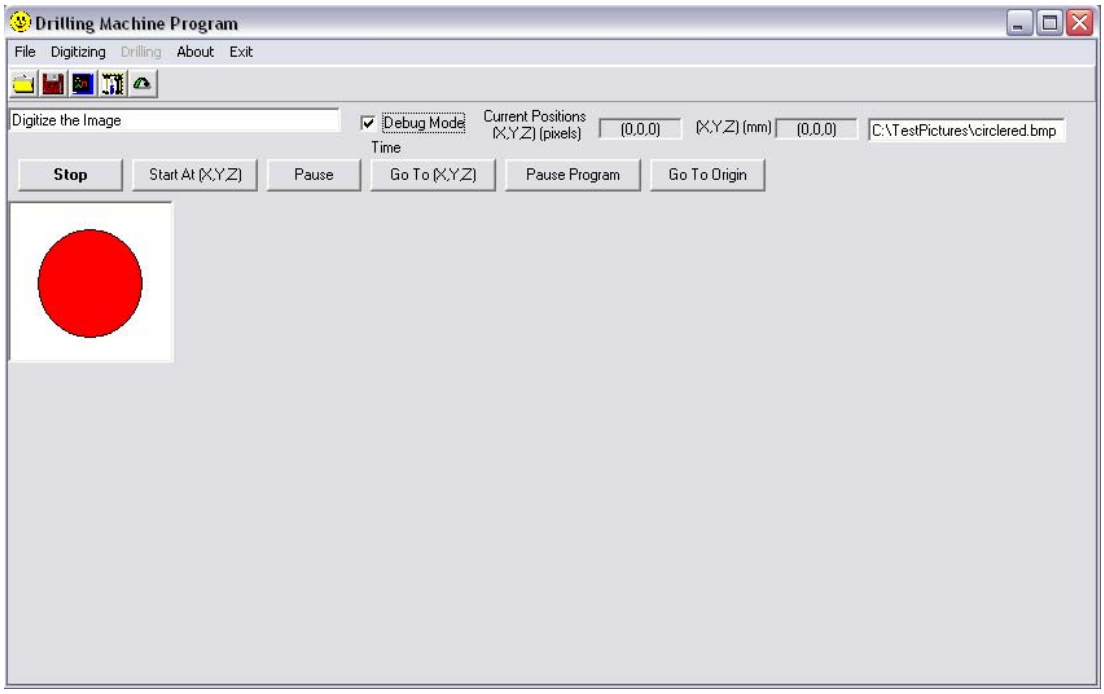


Figure 4.12 Main module of the drilling program

4.1.4.1 Loading the Object

An image file is selected by using the "Load Image File" under the "File" item ("mnuLoadImageFile" is called) which will trigger a "Microsoft Common Control Dialog Box" object to select the image file. The selected image is loaded into a picture box object on the main form named as "DrillPicture". All the calculations and image processing jobs are realized by utilizing this picture box object methods (for example "Point" method is used for accessing the color map of a specific point). With this property of VB, it is possible to load all type of image files (gif, bmp, jpg, tiff, etc.).

There are two critical points to set in the "Properties Window". The "Scalemode" property should be changed to "Pixel" value since the drawings are in pixel unit format and "Autoredraw" property should be set to "False" value to be able to digitize and obtain the whole points of the image even it is larger than the screen.

Note that before loading a new object in order to ensure proper operation, all of the critical variables are cleared by the “ResetAll()” function.

4.1.4.2 Digitizing Two Dimensional Object

“Digitize Min Distance” and “Digitize Top” items under “Digitizing” menu item are enabled after completing the image loading process successfully. The two dimensional object drawing that will be digitized should satisfy the requirements and limitations given section 4.1.1. For both types of digitizing, the “PaintDrill()” (See Appendix A) function is called with the corresponding parameter. At the end of the “PaintDrill()” function, the “ImageMatrix()” variable is filled with the proper values (See Appendix A).

The image is scanned through the columns and after completing columns of a row, the scan row is incremented by one. The first black point met is the starting point for the “Digitize Top” type. For the other type, the starting point is determined after completing the full scan of the image where the starting point will be at the minimum distance with respect to origin. If a proper starting point is determined, then it is painted in red and a counter variable for determining the number of objects is set to one which shows that at least one object exists in the picture.

After finding the first point of the object, the neighborhood points are scanned through “1” to “8” in the order given in Figure 4.13. When a black point is found, the other points in the neighborhood are not scanned anymore. Note that the reason for stopping the scanning process when a proper point is found is speeding up the digitizing of the object. For example, if a proper point is found at the position “1” there is no need to scan the other seven neighbors that will spend unnecessary time. The process repeats itself until no black points exist in the neighborhood.

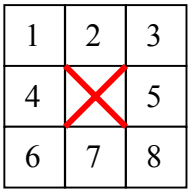
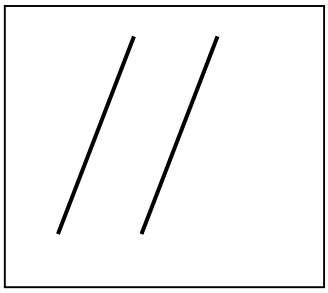


Figure 4.13 The neighborhood scanning order for a point for digitizing a two dimensional object.

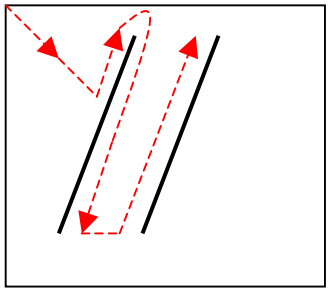
After completing one object, the picture is scanned to determine if any other black point exists. If one is found, then the object number counter is incremented by one and the whole process is started from the beginning for this new object until no black points found.

Digitizing with either “Digitize Min Distance” or “Digitize Top” has a significant importance when the image is not a closed curve. An example of this situation is shown in

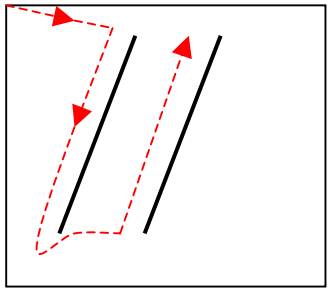
Figure 4.14 where the image consists of two non closed curves. When the image is digitized with “Digitize Min Distance” the path for digitizing and also drilling will be as shown in the figure and so there will be three images detected instead of two. From the view of drilling, this is not only waste of time but as the number of images in the objects is not correct the problem of giving different depths for different images appears.



An image consisting of two non closed curves.



Path for “Digitize Min Distance”



Path for “Digitize Top”

Figure 4.14 Digitizing and drilling path for a non closed curve with “Digitize Min Distance” and “Digitize Top”

4.1.4.3 Digitizing Three Dimensional Object

“3D Imaging” menu item under “3D Menu” is used for digitizing a three dimensional object whose drawing should satisfy the requirements and limitations given section 4.1.1. The image is scanned through the columns and after completing columns of a row, the scan row is incremented by one. The first black point met is the starting point. Then with a similar process in digitizing a two dimensional object, the black part, i.e. the contour, is digitized. For each point on the contour, a “PaintInner()” function is called in order to determine the following layer. The function searches the 4-neighbors (see Section 3.2.4.1) of the point and when a red

point is detected, it is painted to blue. As the contour is a closed one, searching for the 4-neighbors will ensure the existence of a red point. At the end of the closed contour, all of the blue points, which will allow all of the process to start from the beginning, are painted to black.

The reason to use a different order for scanning the neighborhood (see Figure 4.13 and Figure 4.15) is that as the number of digitized layers is increased, the contour starts to look like a rectangular shape. By application of this method, the motors will only move within the object not the rectangle that covers the object [5].

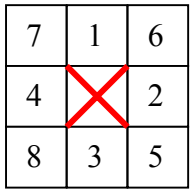


Figure 4.15 The neighborhood scanning order for a point for digitizing a three dimensional object.

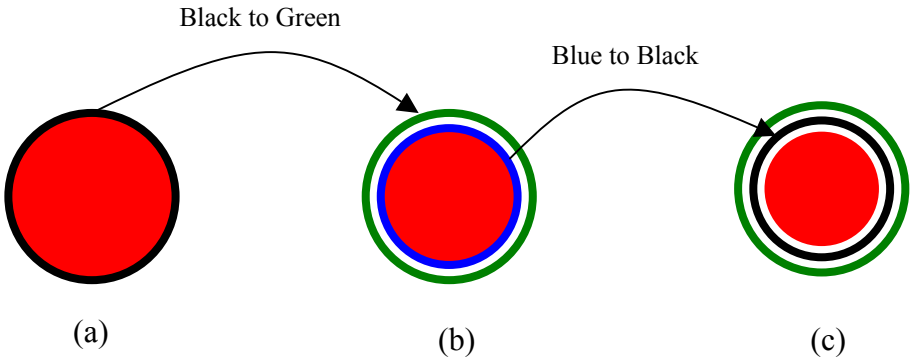


Figure 4.16 Digitizing process of a three dimensional object

4.1.4.4 Saving / Loading the Digitized Object

Digitizing two- or three-dimensional objects creates an identical type of digitizing matrix which keeps the values of X's and, Y's with the corresponding Z

values. These matrix values may be saved to a text file whose path and filename are user-selected.

Loading of a digitized image is in fact loading the digitizing matrix that is identical to digitizing the object. In order to use this property, the image should be loaded as described in Section 4.1.4.1 and after that “Load Digitized Image” menu item under “File” should be chosen.

The aim of using the “saving” and “loading” properties is saving the time of the digitizing process if the same object is desired to be drilled for more than one time.

4.1.4.5 Drilling the Object

The (x, y, z) data in the digitizing matrix is transformed into a new matrix which is sorted with respect to the “Z-Depth” values (each value of the matrix corresponds to a layer of the object) with corresponding X and Y values. The drilling process starts from the smallest Z-depth value for two-dimensional objects and the Z value matching the first layer on the profile file (see Section 4.1.1) for the three-dimensional objects.

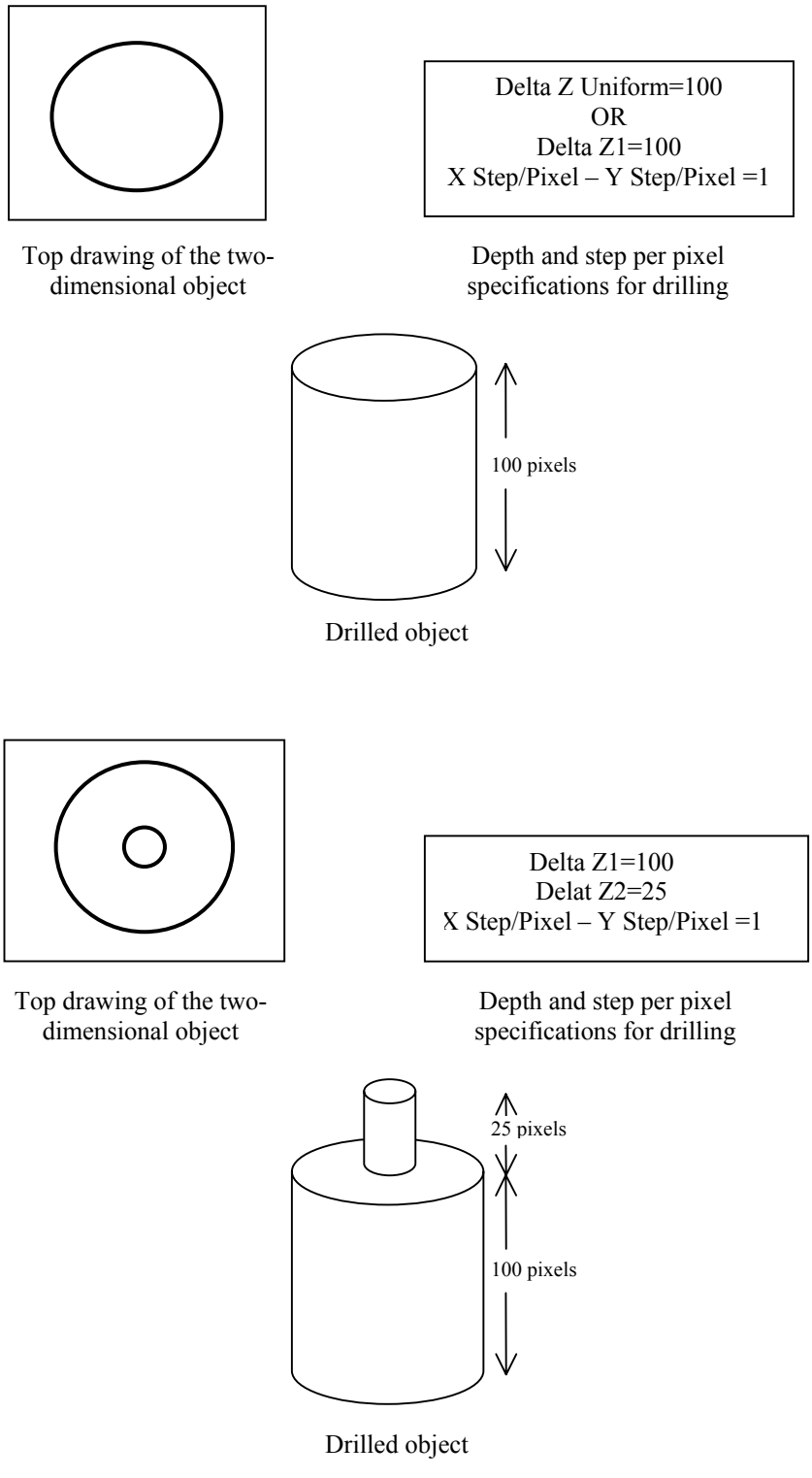
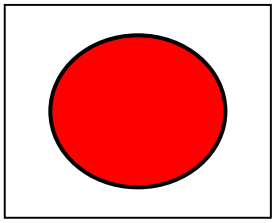
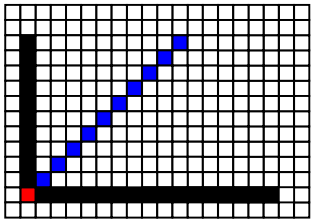


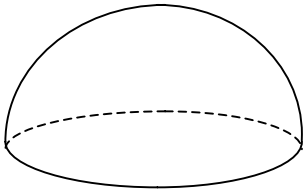
Figure 4.17 Digitizing with two-dimensional method examples



Top drawing of the three-dimensional object



Depth function



Drilled object

Figure 4.18 Digitizing with three-dimensional method example

The drilling process follows the exact path illustrated in digitizing process. It is clear that when a mismatching occurs in the digitizing process, the user should not attempt to drill the object. During the drilling process, the progress bar shows the percentage of the completed part to give an idea about the remaining time to the user. Also the time elapse and the current position information are given on the main module interface (see 4.1.4).

In the case of having a hard drilling material (see 3.1.3) or having a large depth, for not to damage the cutting tools it is better to use the “Repeat Drill” menu item under “Drilling” and drill the object step by step. Also the same object can be drilled again to some other position by shifting the coordinates with “Start At” (see 4.1.2).

In drilling process, the “diagonal movement”, i.e. the movement of the x and y motors simultaneously as long as possible, is used where available as it is obvious that a diagonal movement takes shorter time than the movement of one motor to the

desired position first then the other. As it is seen in Figure 4.19, when the path for the consecutive movement is followed the total time needed is:

$$time_{consecutive} = [(y_1 - y_0) + (x_1 - x_0)] * delaytime \quad (4.3)$$

where the total time for simultaneous movement of the motors is:

$$time_{simultaneous} = \max\{(y_1 - y_0), (x_1 - x_0)\} * delaytime \quad (4.4)$$

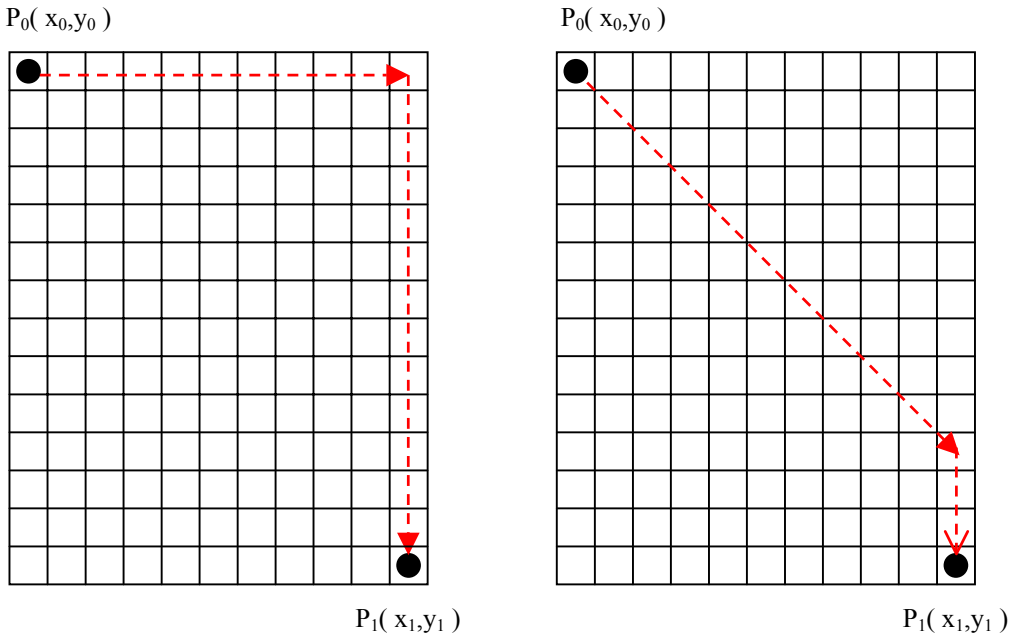


Figure 4.19 Consecutive and simultaneous movement paths for X and Y motors

From the equations (4.3) and (4.4) and Figure 4.19, it is clear that the time to be followed is shortened with the diagonal movement.

At the end of every drilling process, the cutter returns to its starting position i.e. the (0,0,0) point.

4.1.5 "About" Module

The name and version of the program, copyright and contact e-mail address for support take place in the interface of "About" module.

Figure 4.20 About module of the drilling program

CHAPTER 5

RESULTS

5.1 Image Processing Performance

The drilling process follows the exact path illustrated in digitizing process. It is clear that when a mismatching occurs in the digitizing process, the user should not attempt to drill the object. Any kind of mismatch that can be occur in image processing, i.e. in the number of the images or dimensions, can be detected by observing the user information interface window that appears after digitizing the object (see 4.2.2).

Two different methods for digitizing, i.e. minimum distance and top distance options that are mentioned in 4.1.4.2, also improves image processing when the appropriate one is chosen.

Another method for saving time in digitizing process is to use “saving” and “loading” properties (see 4.1.4.4) if the same object is desired to be drilled for more than one time. Thanks to this method there is no need to digitize an object again and again but it is enough to save the matrix that holds the coordinate data of the digitized object.

5.2 Drilling Performance

As the path of the drilling process follows the exact path illustrated in digitizing process, there is no time loss with tracing the points that will never be drilled and the resulting object is much smoother compared with the other algorithms for the elliptical objects.

The “diagonal movement” of the motors, in other word movement of the X and Y motors at the same time as long as possible shortens the drilling time up to %50 (see 4.1.4.5). The “Repeat Drill” option mentioned in 4.1.4.5 also improves the drilling time with holding the previous drilling option values.

The current position information in pixels and millimeters, pause program and drill tracking options, that take place in the “Start Up” module (see 4.2.1), are also the effective factors for time of drilling. As an example drilling time data for an elliptical object, whose top drawing is given in Figure 5.1 with the following drilling options, is given in Table 5.1.

Maximum X Dimension = 286 pixel
Maximum Y Dimension = 144 pixel

Delay X-Y = 5 msec.
Delay Z = 5 msec.

Step/Pixel X-Y = 8
Step/Pixel Z = 1

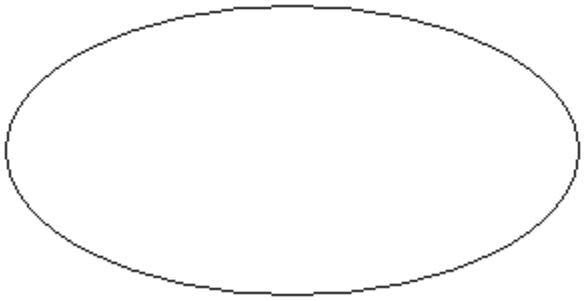


Figure 5.1 Top drawing of an ellipse as a two-dimensional object

As it can be observed from the data in Table 5.1, the minimum time required for this specified drilling process is the one with all options, including “Debug” which means that there will not be a real drilling process but only a simulation on the screen, are selected. When a comparison is made between the debug-off ones, it is seen that the most effective option is drill tracking which can be a trade of especially for drilling processes that are being repeated.

Table 5.1 Comparison of the drilling process time with respect to selected options

Debug	**Current Position (mm)**	**Current Position (pixel)**	**Pause At**	**Track**	**Time Elapsed (sec)**
√	√	√	√	√	418.0391
X	√	√	√	√	427.0512
X	X	√	√	√	447.1094
X	√	X	√	√	443.0012
X	X	X	√	√	439.6016
X	√	√	X	√	441.0005
X	√	√	√	X	439.8891
X	X	X	X	X	465.7695

5.3 Drilled Samples

The samples given in Figure 5.2 through Figure 5.8 illustrate the drilled samples realized by 2D and 3D modeling methods. 2D modeling is more suitable for the objects that have smooth surfaces and for labeling applications where 3D modeling is preferred for the objects that have curved surfaces.

Figure 5.2 A sample of a drilled object by 2D modelling

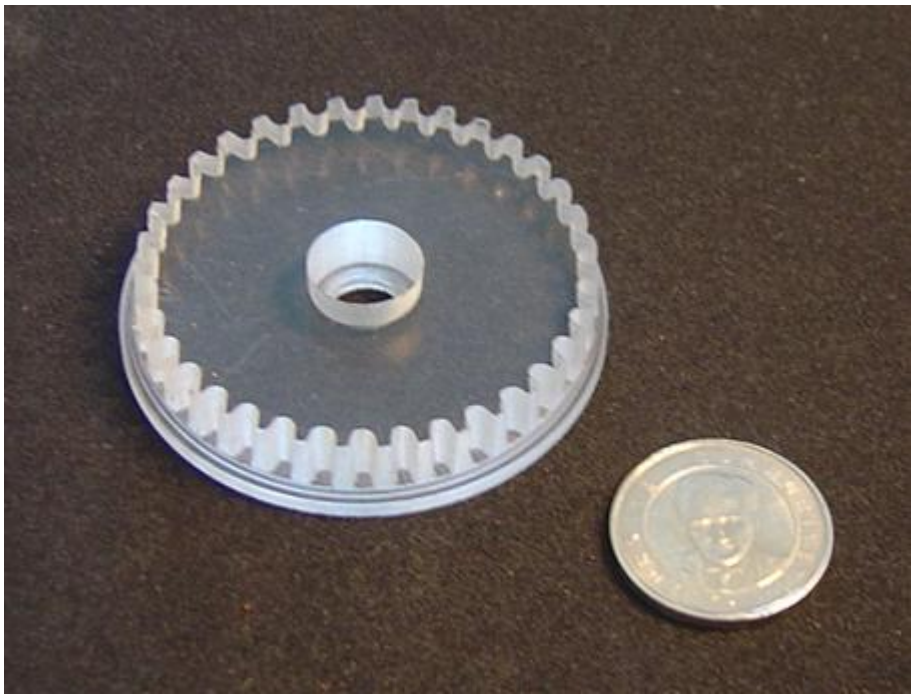


Figure 5.3 A gear realized by 2D modelling

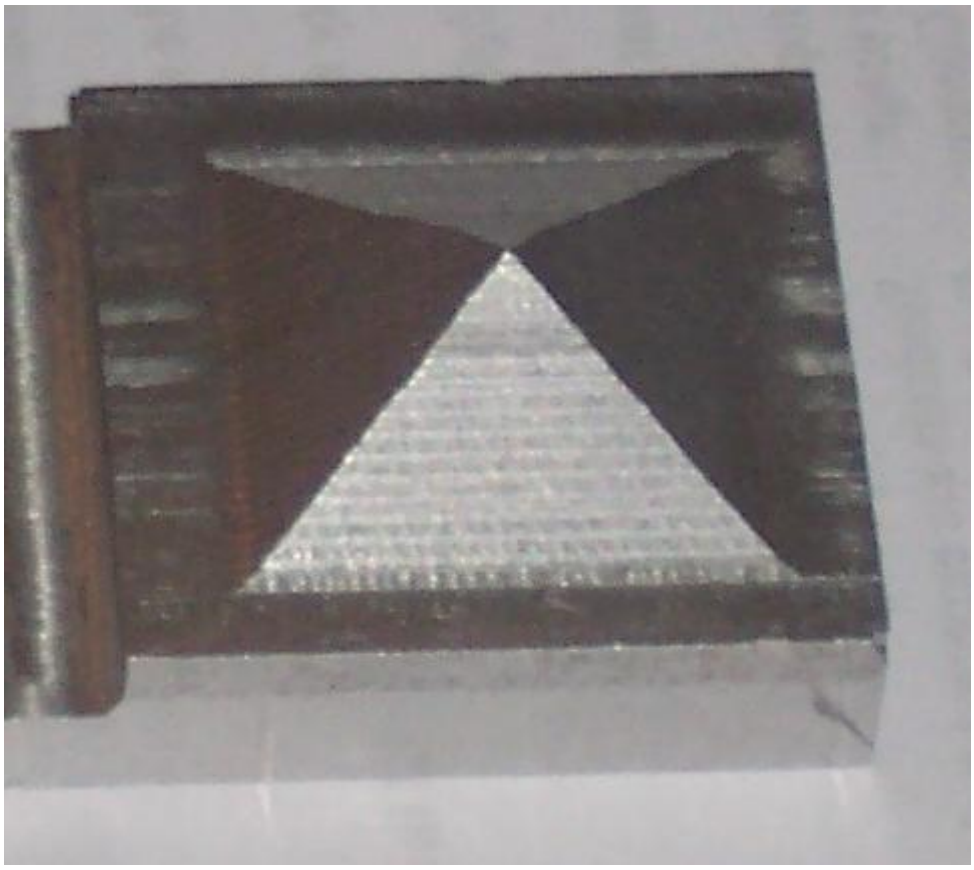


Figure 5.4 A pyramid realized by 3D modelling

Figure 5.5 A dome realized by 3D modelling

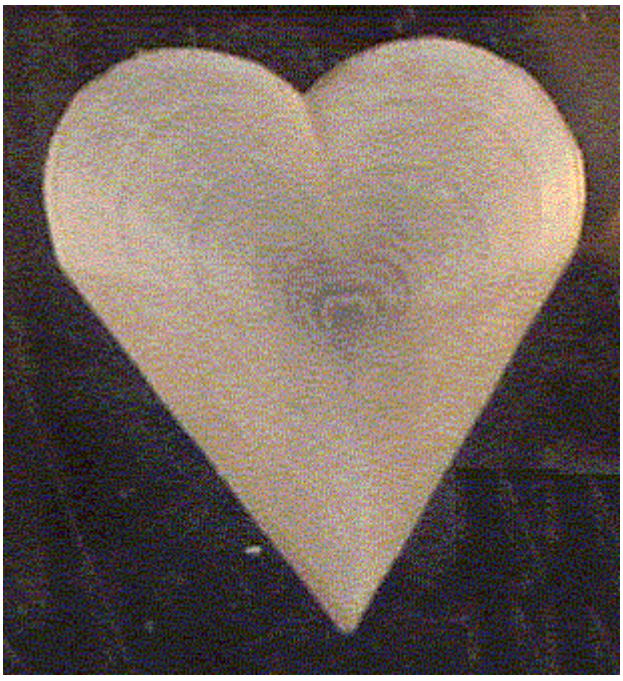


Figure 5.6 A heart realized by 3D modelling

Figure 5.7 A stamp realized by 2D modelling

Figure 5.8 An application of labelling by 2D modelling

CHAPTER 6

CONCLUSIONS

In this study, software for a specific CAD application has been developed under Microsoft Studio Visual Basic 6.0 environment for industrial prototyping. The software is packaged as an executable program so that it requires only the run-time libraries of Visual Basic therefore the licensing problem for a third party software is eliminated.

The software has ability to recognize and digitize two dimensional models of three dimensional objects. By this method the user can easily draw and model an object compared to the three view modeling which will result in saving of time and money consequently. A drawing technician without the skills or education of technical drawing can easily model the objects. But it is clear that objects similar to Figure 1.1 cannot be modeled.

Besides the ease of modeling, the drilling process has been improved significantly. The motors do not scan the entire surface but only move on the contours. So that the motors never move on points that will never be drilled. This method introduces an improvement. Another improvement on the drilling time is achieved by deactivating visual properties such as showing the current position of the table. This brings an improvement about 10% in drilling time. Note that this improvement is tested under a relatively slower PC. The state-of-the-art computer

systems will decrease the benefit of this property because of their fast visual response.

The elliptical objects are digitized and drilled like a spiral shape such as the same depth levels are drilled consequently. By this method the drilled objects are smoother with respect to the other scanning methods.

The drawbacks of the software are clear. The drawings should strictly satisfy the requirements given in Section 4.1.1. After the digitizing process the user is informed of the properties of the digitized object. The user may comment on the information given and make proper corrections

The parallel port of the PC has been used for digital signal generation for the drive circuit so that no extra hardware, that will cause an extra cost, has been introduced. The utilization of special interface software for the parallel port has enabled the program to run regardless of the OS. The previous applications could only run on Windows 95/98 platforms because of the restrictions of the OS. This software, which uses the ActiveX technology, eases the programming burden and handles the application versus OS communication. The demonstration version of IO ActiveX software can be found on the web.

Finally, the implemented software and the hardware have been tested and various prototypes have been drilled. The results are quite satisfying. Especially, labels (names or words drilled on the materials), conical or spherical shapes are satisfactorily realized.

The future work on this topic may be the introduction of a closed-loop control system for the stepping motors. By this method a further improvement of the drilling time may be achieved but the cost and the complexity of the system will obviously increase. Another improvement may be using additional motors on X- and Y-axis to be able to drill an object having the properties similar to Figure 1.1. It is clear that

such kind of an object will require more than one drilling axis and also more than one drawing views.

REFERENCES

[1] Mustafa Bağcı, Prof. Dr. Cemil Bağcı, “Teknik Resim”, 1988.

[2] P.P. Acarnley, “Stepping Motors: A guide to modern theory and practice”, Revised Second Edition, IEE Control Engineering Series 19, 1984.

[3] Benjamin C. Kuo, “Theory and Applications of Step Motors”, West Publishing Co., 1974

[4] SGS Thompson Microelectronics, “Stepper Motor Controllers”, August 1996

[5] Semih Mümin Ateş, “A PC Controlled Three Dimensional Machine Tool Control System”, METU MS Thesis, Dec. 2001.

[6] www.jspayne.com

[7] Roger S. Pressman, ”Software Engineering ”, The McGraw-Hill Companies, Inc., 4th Edition, 1997.

[8] http://mathforum.org

[9] Oliver Faugeras, “Three Dimensional Computer Vision: A Geometric Viewpoint”, MIT Press, 1993.

[10] Berthold Klaus Paul Horn, “Robot Vision”, MIT Press, 1986.

[11] Kemal Şen, “ A PC Based Industrial Position Control System”, ”, METU MS Thesis, May. 2000.

[12] A.E. Fitzgerald, Charles Kingsley, Jr, Stephen D. Umans, “Electric Machinery”, Fifth Edition in SI Units, McGraw-Hill, 1992.

[13] http://www.dai.ed.ac.uk , web page of department of Artificial Intelligence of the University of Edinburg.

[14] Microsoft MSDN Library,2000.

[15] Microsoft Visual Basic 6.0 Language Reference, Microsoft Press, 1998.

APPENDIX A

MODULES AND CRITICAL VARIABLES OF SOFTWARE

PaintDrill():

Synopsis:

Boolean DigType

Description:

Digitizes an image according to DigType parameter. See Section 3.2.4.1.

Returns:

None.

PaintInner():

Synopsis:

Integer x, y

Description:

Searches for 4-neighbors of the point(x, y) and if a red is detected, it is painted to blue.

Returns:

None.

ResetAll():

Synopsis:

None.

Description:

Clears digitizing matrix and variables used for visual purposes.

Returns:

None.

space Type**:**

Type:

x, y, z integer

ImageMatrix:

Type:

space

Dimension:

(1600, 1600)

First column implies the object number and the second one implies the points of the corresponding object.

APPENDIX B

PARAMETERS/SELECTIONS IN THE SOFTWARE

B.1 Parameters/Selections in “Start Up Options"

Name	**Type**	**Comment(s)**
Current Position (Pixel)	Boolean	Show/hide the current position information in pixels
Current Position (mm)	Boolean	Show/hide the current position information in millimeters
Pause Program	Boolean	Enable/disable “Pause Program”
Drill Tracking	Boolean	Enable/disable drill tracking

B.2 Parameters/Selections in “Drilling Options”

Name	**Type**	**Comment(s)**
X Step/Pixel-Y Step/Pixel	Integer	Determines how many step will the motor moves for each pixel
Z Step/Pixel	Integer	Determines how many step will the motor moves for each pixel
Delta Z Profile	Boolean	Type of delta Z
Delta Z Uniform	Boolean	Type of delta Z
Delta Z Uniform	Integer	Determines uniform Z value
Delta Z	Boolean	Type of delta Z
DeltaZ1..DeltaZ20	Integer	Determines non-uniform Z values

B.3 Parameters/Selections in “Go To Coordinates”

Name	Type	Comment(s)
X (Pixel)	Integer	The number of movements in X axis
Y (Pixel)	Integer	The number of movements in Y axis
Z (Pixel)	Integer	The number of movements in Z axis
X+	Button	Moves the X-axis by one (+) step
X-	Button	Moves the X-axis by one (-) step
Y+	Button	Moves the Y-axis by one (+) step
Y-	Button	Moves the Y-axis by one (-) step
Z+	Button	Moves the Z-axis by one (+) step
Z-	Button	Moves the Z-axis by one (-) step
Go To	Button	Enabled only at “GoTo” operation
Start At	Button	Enabled only at “StartAt” operation
Pause At	Button	Enabled only at “PauseAt” programming

B.4 Parameters/Selections in “Main”

Name	Type	Comment(s)
Message Text	Textbox	Messages to the user are given
Debug Mode	Boolean	Enables/disables debug mode

APPENDIX C

MOTOR DRIVE CIRCUIT COMPONENTS

C.1 L298 Dual Full-Bridge Driver

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

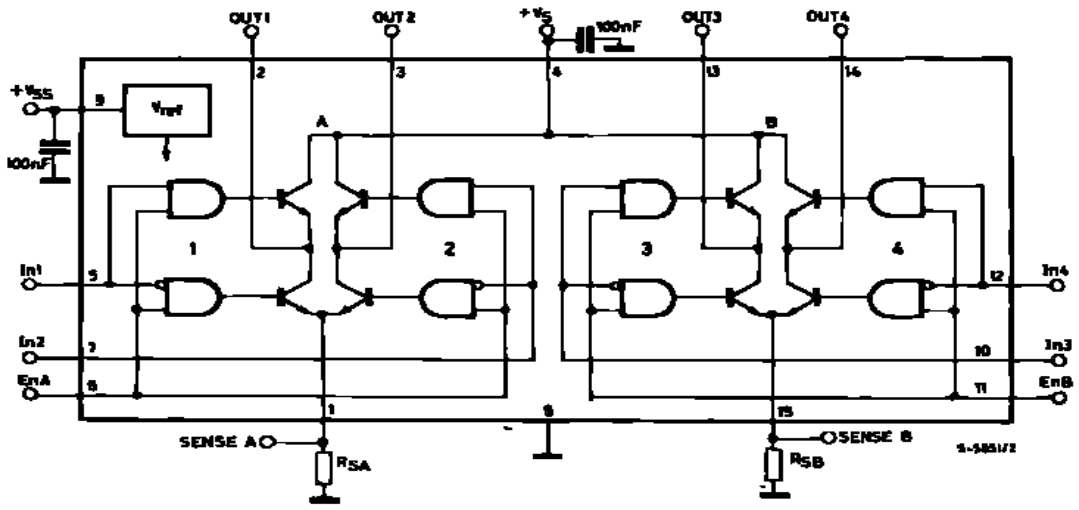


Figure C.1 Block Diagram of L298

Table C.1 Absolute Maximum Ratings of L298

Symbol	Parameter	Value	Unit
V_S	Power Supply	50	V
V_{SS}	Logic Supply Voltage	7	V
V_l, V_{en}	Input and Enable Voltage	-0,3 to 7	V
I_0	Peak Output Current (each Channel)		
	-Non Repetetive (t=100μs)	3	A
	-Repetetive (80% on -20% off; t_{on}=10ms)	2,5	A
	-DC Operation	2	A
V_{sens}	Sensing Voltage	-1 to 2,3	V
P_{tot}	Total Power Dissipation (T_{case} = 75°C)	25	W
T_{op}	Junction Operating Temperature	-25 to 130	°C
T_{stg}, T_j	Storage and Junction Temperature	-40 to 150	°C

C.2 L297 Stepper Motor Controller

The L297 Stepper Motor Controller IC generates four phase drive signals for two phase bipolar and four phase unipolar step motors in microcomputer controlled applications. The motor can be driven in half step, normal and wave drive modes and on chip PWM chopper circuits permit switch-mode control of the current in the windings. A feature of this device is that it requires only clock, direction and mode input signals. Since the phase are generated internally the burden on the microprocessor, and the programmer, is greatly reduced. L297 can be used with monolithic bridge drives such as the L298N or L293E, or with discrete transistors and darlingtons.

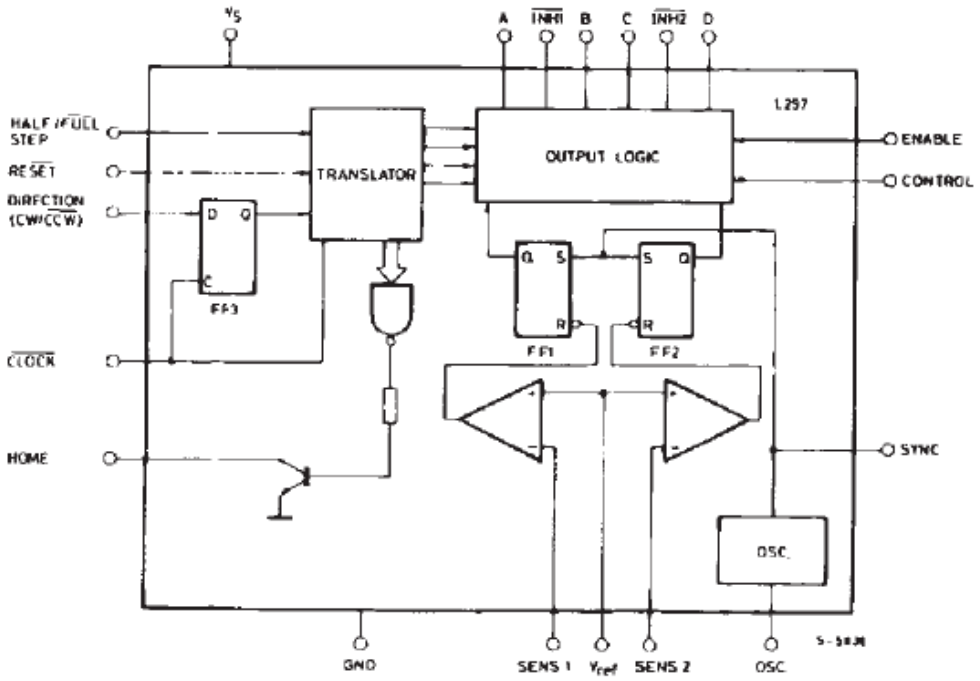


Figure C.2 Block Diagram of L297

Table C.2 Absolute Maximum Ratings of L297

Symbol	Parameter	Value	Unit
V_S	Supply Voltage	10	V
Vi	Input signals	7	V
P_{tot}	Total Power Dissipation (T_{amb} = 70°C)	1	W
T_{stg}, T_j	Storage and Junction Temperature	-40 to 150	°C

C.3 Two Phase Bipolar Stepper Motor Control Circuit with L297 and L298

L297 and L298 can be used as shown in Figure C.3 for various motor drive applications. In the figure, the diodes with 2A current rating are used.

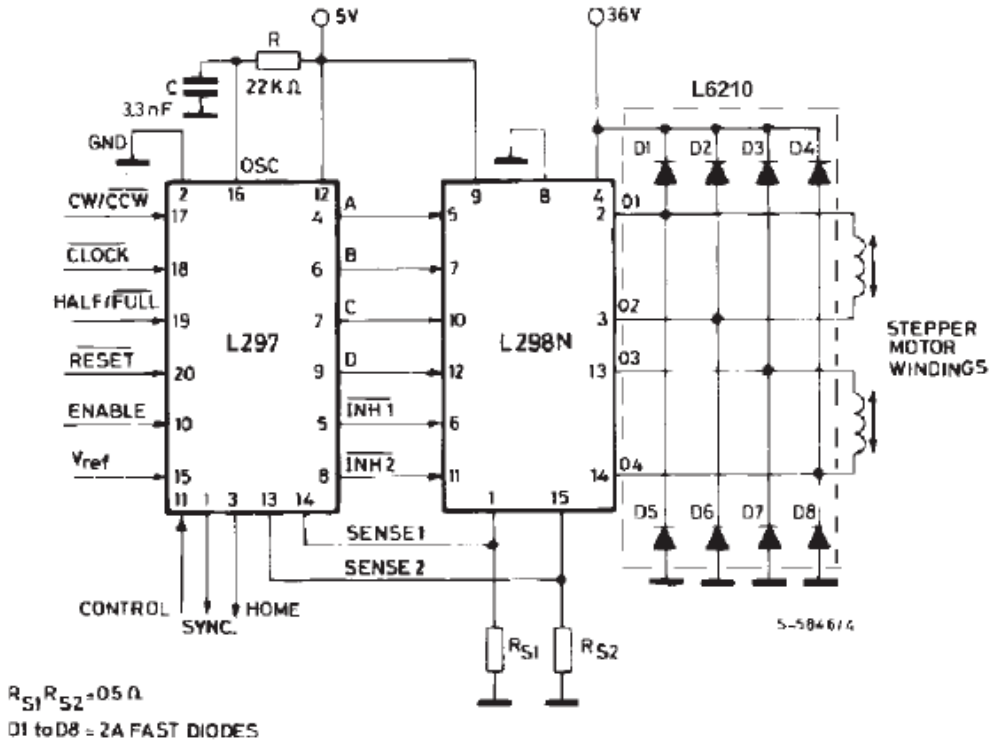


Figure C.3 Two Phase Bipolar Stepper Motor Control Circuit with L297 and L298

APPENDIX D

DECLARATIONS AND RELATIONS OF FUNCTIONS AND SUBS OF THE SOFTWARE

D.1 “Main” Form

Declarations

Dim XX, YY, ZZ As Integer

Dim XXX, YYY As Integer

Dim pausedrill As Boolean

Dim StopDrill As Boolean

Dim PauseDrillProgram As Boolean

Dim lngTotalPoints As Long 'For the Progress Bar

Function CreateMatrixFile()

Declaration

Dim fso, txtfile

Dim count As Integer

Called by

Private Sub mnuRepeatDrill_Click()

Function CalculateTotalPoints()

Declaration

Dim count As Integer

Called by

Function PaintDrill3D(ByVal DigType As Boolean***)***

Function LoadMatrixFile(ByVal strDataFile As String)

Declaration

Dim count As Integer

Called by

Private Sub mnuLoadDigitizedImage_Click()

Function PaintDrill(ByVal DigType As Boolean)

Declaration

Dim x, y, z As Long

Dim mapX(8), MapY(8) As Integer

Dim found, Search As Boolean

Dim xPrev, yPrev As Integer

Dim count, counter As Long

Dim distance As Double

Dim xTemp, yTemp As Integer

Dim EndOfPicture As Boolean

Dim result As Integer

Called by

Private Sub mnuDrillImage_Click()

Public Sub drill2D(x, y, z As Integer)

Declaration

Dim i As Integer

Dim result As Integer

Dim intDiff As Integer

Dim intSimStep As Integer

Dim int1DStep As Integer

Called by

Private Sub cmdStartAtXYZ_Click()

Private Sub cmdGotoOrigin_Click()

Called by

ButtonClick “GoToOrigin”

Private Sub cmdGoToXYZ_Click()

Called by

ButtonClick “GoToXYZ”

Private Sub mnuRepeatDrill_Click()

Private Sub cmdPauseProgram_Click()

Called by

ButtonClick “PauseProgram”

Private Sub cmdStartAtXYZ_Click()

Calls

ButtonClick “Drill Image”

Called by

ButtonClick “StartAtXYZ”

Private Sub cmdStop_Click()

Called by

ButtonClick “Stop”

Private Sub DrillPicture_Paint()

Calls

PaintDrill3D

Private Sub mnuDrillImage_Click()

Declaration

Dim count As Integer

Dim xPrev, yPrev, zPrev As Integer

Dim lngTemp As Long 'For Progress Bar

Calls

Function drillOrigin(x, y, z As Integer)

cmdPauseResume_Click()

ResetAll()

Public Sub drill2D(x, y, z As Integer)

Function drill(x, y, z As Integer)

Called by

Private Sub cmdStartAtXYZ_Click()

Private Sub mnuRepeatDrill_Click()

Private Sub tlbMain_ButtonClick(ByVal Button As ComctlLib.Button)

ButtonClick “Drilling/Drill Image”

Private Sub Form_Load()

Called by

“Main” form when the form is loaded.

Private Sub mnuDigitize_Click()

Calls

ResetAll()

PaintDrill(boolean)

Called by

ButtonClick “Digitize/Digitize Min”

Private Sub mnuDigitizeTop_Click()

Calls

ResetAll()

PaintDrill(boolean)

Called by

ButtonClick “Digitize/Digitize Top”

Private Sub mnuDrillOptions_Click()

Called by

ButtonClick “Drilling/Drill Options”

Private Sub mnuExit_Click()

Called by

ButtonClick “Exit”

Private Sub mnuLoad3DMatrix_Click()

Calls

ResetAll()

PaintDrill3D()

Private Sub mnuLoadDigitizedImage_Click()

Declaration

Dim strDataFile As String

Calls

LoadMatrixFile(strDataFile)

Called by

ButtonClick “File/Load Digitized Image”

Private Sub mnuLoadImageFile_Click()

Calls

ResetAll()

Called by

Private Sub mnuRepeatDrill_Click()

Private Sub tlbMain_ButtonClick(ByVal Button As ComctlLib.Button)

ButtonClick “File/Load Digitized Image”

Function drill(x, y, z As Integer)

Declaration

Dim i As Integer

Dim result As Integer

Called by

Private Sub mnuDrillImage_Click()

Function drillOrigin(x, y, z As Integer)

Declaration

Dim i As Integer

Dim result As Integer

Called by

Private Sub mnuDrillImage_Click()

Private Sub mnuRepeatDrill_Click()

Calls

cmdGoToXYZ_Click()

mnuDrillImage_Click()

CreateMatrixFile()

Called by

ButtonClick “Drilling/Repeat Drill”

Private Sub tlbMain_ButtonClick(ByVal Button As ComctlLib.Button)

Calls

mnuLoadImageFile_Click()

mnuDrillImage_Click()

Called by

ButtonClick “Toolbar”

Function ResetAll()

Called by

Private Sub cmdStartAtXYZ_Click()

Private Sub mnuDigitizeTop_Click()

Private Sub mnuLoad3DMatrix_Click()

Private Sub mnuLoadImageFile_Click()

Function Matrix6Converter()

Declaration

ReDim Matrix6Interface(188, width6, height6)

ReDim ZValueMatrix(1600)

Calls

PaintDrill3D(1)

Function PaintDrill3D(ByVal DigType As Boolean)

Declaration

Dim x, y, z As Long

Dim mapX(8), MapY(8) As Integer

Dim found, Search As Boolean

Dim xPrev, yPrev As Integer

Dim count, counter As Long

Dim distance As Double

Dim xTemp, yTemp As Integer

Dim EndOfPicture As Boolean

Dim result As Integer

Calls

PaintInner(xPrev, yPrev)

PaintInner(xPrev, yPrev)

PaintBlueToBlack

CalculateTotalPoints

Called by

Private Sub mnuLoad3DMatrix_Click()

Function Matrix6Converter()

Function PaintInner(ByVal x As Integer, ByVal y As Integer)

Declaration

Dim count As Integer

Dim mapX(3), MapY(3) As Integer

Called by

Function PaintDrill3D(ByVal DigType As Boolean)

Function PaintBlueToBlack()

Called by

Function PaintDrill3D(ByVal DigType As Boolean)

D.2 “GoTo” Form

Private Sub cmdCancelGoTo_Click()

Called by

ButtonClick “Cancel for Go To”

Private Sub cmdOKGoTo_Click()

Declaration

Dim x, y, z As Integer

Called by

ButtonClick “OK for Go To”

Private Sub cmdOKStartAt_Click()

Declaration

Dim x, y, z As Integer

Called by

ButtonClick “OK for Start At”

Private Sub cmdPauseAtXYZ_Click()

Called by

ButtonClick “Pause At XYZ”

Private Sub cmdXMinus_Click()

Called by

ButtonClick “X- (Decrease X)”

Private Sub cmdXPlus_Click()

Called by

ButtonClick “X+ (Increase X)”

Private Sub cmdYMinus_Click()

Called by

ButtonClick “Y- (Decrease Y)”

Private Sub cmdYPlus_Click()

Called by

ButtonClick “Y+ (Decrease Y)”

Private Sub cmdZMinus_Click()

Called by

ButtonClick “Z- (Decrease Z)”

Private Sub cmdZPlus_Click()

Called by

ButtonClick “Z+ (Decrease Z)”

Private Sub Form_Activate()

Called by

“Go To” form when the form is activated.

Private Sub Form_Load()

Called by

"Go To" form when the form is loaded.

D.3 "Information" Form

Private Sub cmdOK_Click()

Called by

ButtonClick "OK"

Private Sub Form_Activate()

Called by

"Go To" form when the form is activated.

Private Sub Form_Load()

Called by

"Go To" form when the form is loaded.

D.4 "Options" Form

Private Sub btnCancel_Click()

Called by

ButtonClick "Cancel"

Private Sub btnDefaults_Click()

Called by

ButtonClick "Defaults"

Private Sub btnOK_Click()

Declaration

Dim j, k As Integer

Called by

ButtonClick “OK”

Private Sub chkDeltaZNonUniform_Click()

Called by

CheckClick “DeltaZNonUniform”

Private Sub chkDeltaZProfile_Click()

Called by

CheckClick “DeltaZProfile”

Private Sub chkDeltaZUniform_Click()

Called by

CheckClick “DeltaZUniform”

Private Sub Form_Activate()

Called by

“Options” form when the form is activated.

D.5 “Profile” Form

Private Sub cmdOK_Click()

Called by

ButtonClick “OK”

Private Sub cmdSelectProfileFile_Click()

Declaration

Dim x, y, x0, y0 As Integer

Dim result, count As Integer

Dim found As Boolean

Called by

ButtonClick “Select Profile File”

D.6 “Start Options” Form

Private Sub chkCurrentPositionMm_Click()

Called by

CheckClick “Current Position (mm)”

Private Sub chkCurrentPositionPixel_Click()

Called by

CheckClick “Current Position (pixel)”

Private Sub chkDrillTrack_Click()

Called by

CheckClick “Drill Track”

Private Sub chkPauseProgram_Click()

Called by

CheckClick “Pause Program”

Private Sub cmdOK_Click()

Called by

ButtonClick “OK”

Private Sub Form_Load()

Called by

“Start Options” form when the form is loaded.

D.7 “Main” Module

```
Declare Sub sleep Lib "kernel32" Alias "Sleep" (ByVal dwMilliseconds As Long)
Public intXStep, intYStep, intZstep As Integer
Public intPulseDelayXY, intPulseDelayZ As Integer
Public intDeltaZUniform As Integer
Public intDeltaZNonUniform(500) As Integer
Public blnDeltaZType As Boolean  'True for Uniform-False for NonUniform
Public XMax, YMax, ZMax, XMin, YMin, ZMin As Integer
Public intNoOfImages As Integer
Public Const intmmAccr As Integer = 0
Public blnFrmClosed As Boolean 'used for frmGoToInfo form to be closed
Public intCountImage As Integer
'For "Start Options"
Public blnShowCurrentPositionPixel As Boolean
Public blnShowCurrentPositionMm As Boolean
Public blnShowPauseProgram As Boolean
Public blnShowDrillTrack As Boolean
Public blnGotoOrigin As Boolean
'For "Repeat Drill" action
Public blnRepeatDrill As Boolean
```

```
Type space
   x As Integer
   y As Integer
   z As Integer
End Type

Public ImageMatrix() As space 'Digitized Image
Public ImagePoints() As Long 'Digitized Image shown on Picture
Public curpos2D As space
Public PausePosition As space
Public Matrix6Interface() As Long
Public ZValueMatrix() As Long
'3D Options
Declare Function ExtFloodFill Lib "Gdi32" (ByVal hdc%, ByVal i%, ByVal i%, ByVal w&, ByVal i%) As Integer
Public Image1, Image2, Image3 As String
Public crimageno, width1, height1, width2, height2, width3, height3, regions, pauseprog As Integer
Public width4, width5, width6, width7, height4, height5, height6, height7 As Integer
Public startcolred, startrowred, endcolred, endrowred, credx, credy, stepx As Integer
Public matrix1() As Integer
Public matrix2() As Integer
Public matrix3() As Integer
Public matrix4() As Integer
Public matrix5() As Integer
Public matrix6() As Integer
Public matrix7() As Integer
Public sum7() As Long
Public regheight(), borders4(), borders5() As Integer
Public stepsize As Double
Public sumsum6, fcolor As Long
```

Public pixelstepx, pixelstepy, steppixelx, steppixely, steppixelz, drilltime, lastcolscan As Integer

Public pulsedelayy, nextpos, corrected, subfinished, xdiameter, ydiameter As Integer

Public paso, curpos, curdrill, drillno, steppixw6, steppixcol, pulsedelayx, pulsedelayz, lastcoldone As Integer

Public xdist, ydist, zdist, cutter, maxpoint, todrill, state, startcol3, startrow3 As Integer

Public pausex, pausey, pauselayer, curx, cury, curz As Integer

Public pausedrill, fromgoto As Boolean

Public starttime, endtime As Variant