EFFECTIVENESS OF COMPUTER CONTROLLED ROBOTIC PRECISION MANIPULATOR

Muhammad Tarique L. Bhatti,   B.Eng.

A thesis submitted to the Dublin City University
in partial fulfilment for the degree of

DOCTOR OF PHILOSOPHY

Sponsoring Establishment:

Ministry of Science and Technology,
Government of PAKISTAN.

September 1991

ACKNOWLEDGEMENTS

DECLARATION

The author declares that all the work reported in this thesis was carried out by me at Dublin City University during the period of April 1987 to September 1991.

The author also declares that no part of this work has been submitted in support of another degree or qualification to this or any other establishment. The author further declares that he has not been a registered candidate or enrolled student in any of the other academic or professional institution during the course of the research programme.

M. Tarique L. Bhatti

DEDICATION

The author dedicates the contents of this thesis to all sons and daughters of

"SINDH   DHARTEE"

our beloved

"MOTHER"

who greatly expects all their spiritual and moral attachments, not only towards her **glorious existance** but also her prosperity in the time to come.

EFFECTIVENESS OF COMPUTER CONTROLLED

ROBOTIC PRECISION MANIPULATOR

M.T.L. Bhatti (B.Eng.)

ABSTRACT

A robotic precision manipulator has been designed and interfaced with a micro-computer for the manipulation of a workpiece in such a way that 2-D/3-D complex shaped surfaces may be produced using a wire EDM machine in which the cutting forces are relatively negligible.

The manipulator is operated by four AC servo motors, two of them are for the linear manipulation along the X and Y axes and the other two motors are used for the manipulation of the rotary motions, alpha and beta around the X and Y axes respectively. The maximum X and Y axes linear travel for the manipulator is 100 mm and 120 mm respectively, and the angular cutting facility for alpha and beta is 70° and 65° respectively. For carrying out the tests on model material (polystyrene) for the simulated WEDM process a wire cutting unit was also designed, and commissioned on which the cutting wire and a micro-switch is housed.

The interfacing system used for this manipulator has two PC23 indexers and four KS-drives. One PC23 indexer controls three motors and the other controls the fourth motor. There are approximately 80 PC23 commands which can be used for setting the process operating modes and motion parameters. There are approximately 40 KS-drive commands for setting the servo conditions on the KS-drive for system optimisation and to match the operating conditions described for the PC23 indexer. Other additional facilities offered by the interface system were also utilized by designing the programmable voltage regulator (PVR) circuit to change the voltage in the cutting wire through the micro-computer based software during the generation of the shape. The micro-switch on the cutting wire unit is installed and connected with the PC23 indexer to check if the wire cutting rate is less than the workpiece feedrate so that a signal can be sent to the computer for retracing the workpiece cutting path.

A number of programs were developed to generate different 2-D/3-D complex shapes using the model material.

The software developed, describes the shape geometry

sizes, workpiece feedrate and voltage allowed to the cutting wire on user's choice.

The effectiveness of the manipulator, interfacing system and software was studied qualitatively and quantitatively and was found to be very satisfactory. For carrying out the tests on a real WEDM machine, the hardware and software will need to be modified.

The commercially available WEDM machines cost over one hundred thousand pounds with angular cutting facility of ±30° only at 12 mm thick workpiece. The present robotic precision manipulator offers greater angular cutting flexibility of up to ±70° at 50 mm thick workpiece with around 25% cost of these commercially available WEDM machines. The components which are not possible to be manufactured using these costly WEDM machines can easily be manufactured by using this robotic precision manipulator.

CONTENTS

VOLUME I

VOLUME II

APPENDICIES :

APPENDIX A: CALCULATIONS RELATED TO CHAPTER TWO

INDEX TO FIGURES

(xv)

INDEX TO PLATES

(xvii)

INDEX TO TABLES

NOMENCLATURE

A	Area (m^2)
a	Linear acceleration (m/s^2)
b,h,l	Length (Meter)
d	Diameter (m)
F	Force (N)
I	Moment of inetia (m^4)
J	Polar moment of inertia (Kgm^2)
k	Radius of gyration (m)
m	Mass (Kg)
n	Factor of safety
r	Radius (m)
T	Torque (N.m)
V	Volume (m^3)
v	Linear velocity (m/sec)
W	Weight (Kg.)
α	Angular acceleration (Rad/s^2)
α, β	Angle (Radians)
Ω	Angular velocity (Rad/s)
μ	Coefficient of friction
ϵ	Efficiency
δ	
σ	
τ	

CHAPTER ONE

INTRODUCTION

1.1. NUMERICAL CONTROL

Numerical Control **(NC)** is a form of programmable automation in which the process is controlled by inserting predefined data in the form of numbers, letters, and symbols. Probably the most universally accepted definition of numerical control is that quoted in **(1)** (Electronics Industries Association (EIA)), which defines it as "System in which actions are controlled by the direct insertion of numerical data at some point. The system must automatically interpret at least some portion of this data."

There are three basic elements of an operational numerical control system **(2)**. The sequence of these three elements is shown in **figure 1**. These components are named as (i) Program of Instructions, (ii) Controller Unit and (iii) Machine Tool.

1.1.1. PROGRAM OF INSTRUCTIONS

The program of instructions is the detailed step by step set of directions which tells the machine tool what to do. It is coded in numerical or symbolic form

on some type of input medium that can be interpreted by the controller unit The most common input medium is punched tape.

In a typical NC system, the engineering drawing of the workpart must be interpreted in terms of manufacturing processes to be used. It also lists the machines through which the part must be routed in order to accomplish the sequence of operations. This step in NC system is referred to as process planning Secondly, the numerical data, which contains the sequence of machining steps to be performed by NC, for producing a part of the job is maintained on a punched tape and is called part programming (1) The part program is arranged in the form of blocks of information, where each block contains the numerical data required to produce one segment of the workpiece The punched tape is moved forward by one block each time the cutting of the segment is completed The block contains in coded form, all the information needed for processing a segment of the workpiece, the segment length, its cutting speed, feed etc. Dimensional information (length, width, and radii of circles) and the contour form (linear, circular or other) are taken from an engineering drawing. Dimensions are given seperately for each axis of motion. Cutting speed, feedrate, and auxiliary

functions (coolant on and off, spindle direction, clamp, gear changes etc.) are programmed according to the surface finish and tolerance requirements.

Other forms of input media have been used including punched cards, magnetic tape, etc. Now a days computer assisted input media are very common One of the methods involves manual entry of instructional data to the controller unit and is famous with the name of manual data input **(MDI)** This is appropriate only for relatively simple jobs where the order will not be repeated. Another medium of input is by means of direct link with the computer to a number of NC controllers and is known as Direct Numerical Control **(DNC)** The third computer assisted media of data input is Computer Aided Design **CAD,** in which computer assisted graphics facilities offered by commercially available packages generate data, tool path and all other related information. This is the integrated form of Computer Aided Design and Computer Aided Manufacturing **CAD/CAM.** Another form of input medium is known as Voice Numerical Control **(VNC) (2),** which involves vocal communication of the machining procedure to a voice-input tape preparation system. This form of input medium eliminates the manual programming, typing or manual tape verification procedure, and saves time by up to 50 percent

1.1.2. CONTROLLER UNIT

This is the second basic element of the **NC** system. The operation of NC machine tool is controlled by an electronic control system which outputs the analog or digital command signals and receives signals from feedback transducers. The commands necessary to direct the machine operation are punched on a paper tape, which is then fed via a paper tape reader which forms the interface between the electronic control system and the operator (3).

The typical elements of a conventional NC controller unit include the tape reader, a data buffer, signal output channels to the machine tool, feedback channels from the machine tool, control console, and the sequence controls to coordinate the overall operation of the foregoing elements (2). The tape reader is an electromechanical device for winding and reading the punched tape containing the program of instructions. The data contained on the tape are read into the data buffer. The purpose of this device is to store the input instructions in logical blocks of information. A block of information usually represents one complete step in the sequence of processing elements. The signal output channels are connected to the servomotors and other controls in the machine tool. Through these channels, the instructions are sent to the machine tool from the

controller unit. To make certain that the instructions have been properly executed by the machine, feedback data is sent back to the controller via the feedback channels.

The sequence controls involve coordination of the activities of the other elements of the controller unit. The tape reader is actuated to read data into the buffer from the tape, to send signals to and from the machine tool, and so on. The controller console contains the dial and switches by which the machine operator runs the NC system It may also contain data display to provide visual information back to the operator.

1.1.3. MACHINE TOOL

This is the component of the NC system which performs the useful work. In the most common example of an NC system, one designed to perform machining operations, the machine tool consists of the worktable and spindle as well as motors and controls necessary to drive them. It also includes the cutting tools, work fixtures, and other auxiliary equipments needed in the machine operation (2).

There are two basic motion controls of NC system according to the type of the machine known as point to point (PTP) and contour motion (1)

In PTP the objective of the machine tool control system is to move the workpiece to a numerically defined position, and perform the machining operation. After completion of the machining operation the workpiece moves to a new point, and the sequence of actions is repeated. Whereas in the contouring system, the tool is cutting while axes of motion are moving. All axes of motion might move simultaneously, each at different speed. When a linear path is required the axial velocity changes. In contour machines the position of the cutting tool at the end of each segment together with the ratio between the axial velocities determines the desired contour of the part, and at the same time the resultant feed also effects the surface finish

NC machines range in complexity from simple tape-controlled drill presses to highly sophisticated and versatile machining centres. The NC machining centre was first introduced in late 1950s. It is a multifunctional machine which incorporates several time saving features into a single piece of automated production unit. A machining centre is capable of performing a variety of different operations, drilling, tapping, reaming, milling, and boring. It also has the capacity to change tool automatically under tape command. A variety of machining operations means that a variety of cutting tools are required. The tools are kept in a tool drum or other holding

device. When the tape calls a particular tool the drum rotates in order to position the tool for insertion into the spindle. The automatic tool changer then grasps the tool and places it into the spindle chuck. Another capability of the NC machining centre is workpiece positioning. The machine table can orient the job so that it can be machined on several surfaces, as required. Some of the machining centres have the flexibility of having two tables or pallets on which the workpiece can be fixtured so that while the machining sequence is being performed on one table the operator can be unloading the previously completed piece , and loading another one.

1.2. HISTORICAL BACKGROUND OF NC SYSTEM

During world war II the Parsons Corporation had used calculated machining tables (i.e. Tool position numerical data) to move the milling machine table in the longitudinal and transverse directions simultaneously with the aid of two operators (4). On the basis of his experience in machining profiled parts, John Parsons, of the Parsons Corporation proposed that the three dimensional tool-position data can be generated for the profiles part and then be used to control the machine tool motion On the basis of his proposal and technology acheived at that time; William T. Webster, and a few engineers in the Air Material Command concluded that an integration of the

digital computer and high performance servomechanism was required for the new high-precision profile machining technology (5).

The initial contract to study the feasibility of computer control of a machine tool was awarded to the Parsons Coporation, which subcontracted to the servomechanism laboratories of Massachusetts Institutes of Technology (MIT) in October 1949, where the initial prototype NC machine was built using vacuum tubes for the controller hardware. These components were so large that the control unit consumed more space than the machine tool (2). The MIT study confirmed the feasibility of a system that could meet the performance required by high precision profile machining. The first vertical milling machine with three axes simultaneous tool movement, controlled by a new type of control system, was built at MIT in 1952 It had an analog-digital hybrid control unit that used a binary perforated tape as the medium for storing the machining program, and was called numerical(ly) control(ed) machine. This machine demonstrated that a part could be made at much higher speed and with accuracy and repeatability three to five times greater than could be acheived by any previous machine (5).

During 1952 to 1955, further research was carried out at MIT under contract with U.S. Air Force to test and evaluate the new NC machine control and to study it's application to other machine tool. Development of NC

programming techniques was another important subject of the research. The Air Force then decided, in 1956 to sponsor the construction of 100 large NC milling machines for the manufacture of aircraft parts for US $60 millions to four different groups of machine tool controller manufacturing teams (5).

The successful application of NC depended on two major factors, the improvements of NC machine tool controller system and the development of software programming aids. The structure, configuration, and design of modern NC machine tools have changed considerably in comparison with those of convensional machine tools. The feed drive system was the vital part of the NC machines, because it determined the position and contouring accuracy of the machine. The requirements of the feed-drive system used on NC machine tools were high precision and quick response. Slideways of antifriction design with rolling elements between the slideways and the moving parts were used to reduce the friction and the stick-slip which effects accuracy with convensional design (6,7) As the basic driving element, the recirculating ball screw, of antifriction design, replaced the traditional Acme screws. Antibacklash driving mechanisms were developed to minimize the positioning error resulting from the backlash between the driving and the driven elements Seperate direct current motors were used for motion in different axes instead of the central drive design of the conventional machine tools (8).

High precision position measuring and feedback systems
for both angular and linear motions were developed and used
for NC machines because they were necessary for the
realization of closed-loop control (9,10).

Additional motions including linear and rotational,
in directions other than the classic X,Y, and Z axes were
incorporated into NC machines to cope with complex contour
machining. Moreover, automatic tool selection and
changing systems were developed to allow the NC machine to
cut a part with different cutting tools within one hold A
new kind of machine, called an NC machining centre, came
onto the scene in late 1950s (11). It combined the
functions of several conventional machines.

In the mean time, the structural configuration of the
NC machine tool also went through significant change.
Emphasis was given to the stiffness of the machine frame,
greater support for the saddle and turret, and easier
removal of the swarf, as these factors were vital to high
precision machining and to a high rate of metal removal.
For both versatility and simplicity, the modular design
concept has been the trend (12) in the design of NC machine
tools since the late 1960s.

Another important aspect in the development of NC
machine tools was related to the NC control system, called
the NC controller unit. NC controller unit can be divided
into two main types, namely open and closed-loop control

types. The open type does not allow positional errors to be compensated for and is used basically for machines that require positional or point-to-point control of low accuracy. The most modern **NC** machines are based on closed-loop control, which compensates for the positional error on the basis of feedback from position measuring unit, thereby ensuring the accuracy and repeatability needed for positional and profile following control **(8)**.

With the development of electronic technology, second and third generation **NC** controllers were constructed with digital circuitry using individual transistors and integrated circuit boards. The basic control functions were realized through the hardware, a fact that results in the high cost of **NC** controllers and prevented them from having more sophisticated functions. The development of the computer technology brought about a continual decrease in the cost of computer hardware and by the end of 1960s, the Read Only Memory **(ROM)** technology could be applied to NC controllers. A sequence of operation instructions could be stored in ROM and could be accessed and executed by the machine's control unit. As a result, an NC controller could have more functions without relying on the addition of more hardware, a stored program was the only thing needed. The **NC** controller became more sophisticated, but less expensive **(8)**. As the decrease in the size of micro-processors and computers continued, it became possible in 1970s to incorporate a dedicated computer in an NC controller, a technique called Computer Numerical

Control **(CNC)**. The tape, either paper or magnetic strip was no longer the only means to store the **NC** program for a **CNC** controller. A program could either be stored in the memory unit of the controller or be received from a seperate computer. The program stored in the **CNC** controller could also be modified. The CNC controller also provided online diagnosis of machine status and easy communication with various input output devices and computers.

Two approaches were developed to realize communications between **CNC** controller and computer With Distributed Numerical Control **(DNC)**, a complete part machining program can be sent from a computer and stored in the CNC controller before it is executed. It can also be sent to an **NC** controller statement by statement while being executed. The method of sending an **NC** program in real time while the part is being machined is Direct Numerical Control **(DNC)**. The difference between these two approaches is that the program size for CNC is limited by the capacity of the memory unit of the **NC** controller. With **DNC**, the operation of the NC machine depends on the signals sent to the computer. Usually a central computer is used for the control of several **NC** machines. Thus the operation of the **NC** machines relies on the satisfactory operation of the control computer.

The precise data regarding consecutive tool positions in a machining operation should be given in the **NC** program. However, for parts of complicated shapes it is not possible to calculate the tool position data manually. The difficulty in the programming arises from the need for translating the data into the codes required by different **NC** controllers **(8)**.

In 1955 a prototype **NC** programming system, developed at **MIT**, was tested on the Whirlwind computer to demonstrate the feasibility of using computers to assist in NC programming. In 1957 a joint effort was initiated by members organisation of the Aerospace Industries Association to develop a computer program that could assist in preparing **NC** tapes for all kinds of NC systems. The development of this program was carried out by a group of research mathematicians from the aircraft companies under the co-operation of MIT This computer program, completed in late 1958, was named Automatically Programmed Tool **(APT)**. It was designed for use on an IBM computer system. The initial version had many errors, and the work of testing, debugging, and improving the APT program was not completed until June 1960. Later it was further refined as the well known **APT III** program or processor. As the largest software package used in the industry, in early 1960, APT was also the most used software on the mainframe computers installed in those aircraft plants **(5)**.

The output from the **APT** processor, which is the description of the tool position and the desired sequence of operations and is known as the Cutter Location DATA **(CLDATA)**, should be in the standard format that is independent of the **NC** systems. It must further be translated by another computer program, called the post processor, into the specific NC codes required by the **NC** machine to be used.

In 1961, the APT Long Range program, was formed to improve and to maintain the APT software package. The task was assigned to the Illinois Institute of Technology Research Institute. Later the program became international in scope, with participants from a number of European countries and Japan **(13)**.

The early version of APT was designed basically for three dimensional or multi-axes profiling. A part machining program was written in an English like language called the APT language, to describe the geometry of the part, the cutter paths, and the machining specifications. For many simple machining operations involving point-to-point motion and the motion cycles of two dimensional machining, the language was not so convenient for the user. Another disadvantage of the APT for a smaller user was the requirement of a large mainframe computer, which was very expensive in 1960s, to run APT Therefore, a number of NC programming and processing programs were developed in both the United States and

European countries to simplify the APT processor, to lessen the computer requirements, and to include some functions that were not available in APT. Many of these languages were based on APT **(14)** or on concept similar to APT. These include for example, ADAPT, EXAPT, IFAPT, and COMPACT-II which have been in general use. Now a days APT is the only **NC** programming language that has gained worldwide acceptance, and has been standardized in the United States since 1974 Currently, APT is supported by the IBM Corporation **(15)**.

On the basis of geometric entities specified by the APT geometric definition statements. The rapid development of Computer Aided Design **(CAD)** technology in 1960s made it possible for designers to construct engineering drawings on a Cathode Ray Tube **(CRT)** screen and to create a geometric model within the computer. A geometric entity defined by a system within a computer is represented by a group of data, the parameters of the mathematical functions or equations describing the geometric entity. In otherwords such data representation of a part within the computer are so called the **CNC** model of the part. The data of a **CAD** model can be further used to define an **NC** cutter path with the aid of certain **NC** programming software Thus if **CAD** system is provided with the necessary function to define an NC cutter path based on the **CAD** model, one can also define an **NC** cutting process directly on the drawing displayed on the **CRT** screen Such a system is usually called Computer Aided

Design / Computer Aided Mamufacturing (CAD/CAM) system. Currently a good number of general and NC oriented CAD / CAM systems are available on the market (8)

NC technology was initially developed for controlling metal profiling operations. Today its application has already gone beyond this scope. Beside its applications in metal cutting, which includes turning, milling, drilling, grinding, and Electric Discharge Machining (EDM), NC technology is also used in welding, flame cutting, metal forming (eg. sheet metal working, rolling and forging), inspection and measurement process (16). NC has also been used in industries other than metal working such as wood working, textile, plastics, and electronics (10). Robotics is also one of the recent important application of NC since the same principles of programming and control philosophies apply.

1.3. ADVANTAGES AND DISADVANTAGES OF NC SYSTEM

Numerical system has significant advantageous features over conventional machining processes, which could never have been achieved without present developments in NC technology. These features include (2).

1. Reduced nonproductive time

NC system increases the proportion of time that the

machine is engaged in the actual process It accomplishes this by means of fewer steps, less time in setting up, reduced workpiece handling time, automatic tool changes on some machines, improved cutting efficiency and controlled speeds and feeds (17).

2. Reduced fixturing

NC requires fixtures which are simpler and less costly to fabricate because the positioning is done by the NC tape or other input media rather than the jigs and fixtures.

3. Greater manufacturing flexibility

It is less difficult to adapt to engineering design changes, alterations of production schedule change overs in jobs for rush orders, and so on (2).

4. Improved quality control

NC is ideal for complicated workparts where the chances of human mistakes are high. NC produces parts with greater accuracy, reduces scrap, and lowers inspection requirements. Average scrap decreases from NC, ranges from 31% to 44% (depending on the machine tool.) (18).

5. Reduces inventory and floor space

Since one NC machining centre can often accomplish the production capability of several conventional machines, the amount of floor space required in an NC shop is usually less than in a conventional shop. Owing to fewer setups and shorter lead times with NC, the amount of inventory carried out by the company is reduced.

Beside all of these advantages of NC system which makes it more attractive towards production and profitable trade, companies have to pay attention towards few of the disadvantages as well, like

1. Relatively higher investment

NC technology costs more to buy than its non-NC counterpart. The higher cost requires manufacturing managements to use these machines more aggressively than ordinary equipment

2. High maintainance cost and skilled NC personell

NC technology is more complex and these machines are used almost continuously, therefore maintainance problem can become more acute because of a more

complicated system. A special crew is desirable **(1)**.

As *NC* system uses fixed logic hardware, it carries

afew more disadvantages **(3)** as well

3. Part programming can not be stored in any memory to
   produce the required number of components. It is
   necessary to read the part program tape as many times
   as the number of components to be produced.

4. Debugging and amendments of part program is difficult.
   It is not possible to modify the program in on-line
   mode.

5. Conventional **NC** control systems are rather inflexible,
   because it is designed to suit one particular machine
   or range of machine tools.

6. Fault diagnosis and correction is difficult and time
   consuming.

1.4. CNC AND DNC SYSTEMS

Computer Numerical Control **(CNC)** is an NC system that
utilizes a dedicated, stored program to perform some or
all of the basic control functions.

The major function of the computer used as part of a
numerical control system is to replace the fixed hardware
controller, which has a number of sub-systems for carrying
out different tasks. Part program tape, prepared manually

or with computer assistance, is read and stored into memory (3). Secondary storage devices such as floppy disks or cartridges may be used to store a large number of programs and recall them, as and when required, and can be used as many times as necessary to produce the complete batch quantity. Software is used to carry out the required interpolation, and it is possible to use linear, circular or parabolic mathematical functions for carrying out this interpolation. In contrast, conventional **NC** controllers require the use of hardware interpolation. The use of a computer as a part of the NC system results in very considerable flexibility and computational capability. **Figure 2** shows the general configuration of a **CNC** system.

The use of software for controlling NC machine tools means that further control functions can be incorporated simply by programming, whereas the conventional **NC** controller would require hardware modification, which is more expensive **(3)**.

The **NC** tape can be corrected and even optimized (i.e., tool path, speeds, and feeds) during tape tryout at the site of the machine tool **(2)**.

Beside all the above mentioned improvements gained by using a micro-computer as an integral part of **NC** control system, the CNC system offers increased security functions, possibilities to develop an adaptive control, and reduced lead time particularly with computer aided

graphics NC **(5)**. A **CNC** system is more compatible with the use of computerized factory-wide manufacturing **(2)**. Being computerized, NC systems open the door towards more practical computerized systems like Flexible Manufacturing System **(FMS)**.

Adaptive Control in a machining operation denoting a control sytem that measures certain output process variables and uses these to control speed and/or feed. Some of the process variables have been used in adaptive control machining systems including spindle deflection or force, torque cutting temperature, vibration amplitude, and horse power. Adaptive control machining originated out of research in the early 1960s sponsored by the U.S. Air Force at Bendix research laboratories. Now a days it is typically integrated with an existing **CNC** system **(2)**.

The temperature generated during cutting is usually dependent on the cutting speed, and by measuring the temperature of the tool tip it is possible to maximize the tool life by automatically varying the cutting speed to suit the conditions. Another method developed for use on turning centres uses a force sensor placed under the tip of the tool. The feed rate is automatically adjusted until the optimum conditions are acheived If the tool should fail, the force will increase very rapidly and this will cause the sensor to send a signal to switch off the main motor and apply a brake sensing the spindle to stop rotating within one revolution **(5)**.

Direct Numerical Control (DNC) system contains a number of numerically controlled machines in real time. All the machines are linked to a mainframe central computer which sends the information to the individual machines as required, and also involves data collection and processing from the machine tool back to the computer in real time. There can be a number of different types of machines linked to the one main frame computer. The computer is programmed to be able to select the order of manufacture of components. **DNC** is capable of being integrated into the running of a complete factory, provided that the orders for equipment or parts are entered into the computers memory **(5)**. **Figure 3** illustrates the general configuration of basic **DNC** system.

There are two main types of **DNC** system configuration **(2)**. In the first type , the computer is directly linked with **NC** regular controller unit. The replacement of the tape reader by the telecommunication lines to the **DNC** computer is called Behind-Tape-Reader **(BTR)**. This arrangement is shown in **figure 4** . The controller unit uses two temporary storage buffers to receive blocks of instructions from the **DNC** main computer and converts them into the machine's actions. While one buffer is receiving the block of data, the other is providing the control instructions to the machine tool. One advantage of this system is that there is only one point of control **(5)**

In other systems, the regular controller unit is

replaced with a special machine control unit (MCU)   The configuration of this system is shown in **figure 5**. The MCU configuration achieves superior balance between accuracy of the interpolation and fast metal removal rates than is generally possible with **BTR** system of DNC. As this **MCU** is softwared, it takes some of the burden off the central computer and offers more flexibility and greater computational capability.   As most of the **NC** machines are sold with a micro-computer as an integral part of the NC system (CNC), the **CNC** computer serves much the same role as a special machine control unit **(MCU)**, when incorporated the **CNC** into a **DNC** system.

1.5. ROBOTICS

The word **ROBOT** comes from Czechoslovakian word "robotnik" meaning "slave" It was coined in the play opilek by playwright Karel Capek in 1917.   Then in 1927 German director Fritz Lang made a film "Metropolis" and introduced the first female robot. Afterwards in 1938 Isaac Asimov coined the term robotics in his science fiction novels.   On 29th March 1954 the first robotic patent, No. 781465 was granted in England.

By 1950, George Devol had patented a new form of magnetic recording and had worked on the development of large scale random access memories and ultra high printers. He worked day and night to apply digital control to a "manipulator" which could be programmed on the job.   The

machine tool was multi-axes, meaning it could access components from many angles. As 1954 passed, Devol was deeply concerned with over 40 patents on tooling and transfer systems, which would later be dropped in favour of a robot (19).

In 1956 Joseph Engelberger, met George Devol, and was talking about Isaac Asimov's conception of robotics. Engelberger who was the general manager of a small aerospace division at Manning, Maxewell and Moore, in Stamford, Connecticut went into experimentation with robotics as a side line for his operation. By 1957 Manning, Maxwell and Moore were getting out of aerospace business. Engelberger enlisted the aid of Norman Shafler, the founder of the military vehicle manufacturer, consolidated Disel Electric Company, to purchase the 160-worker aerospace division (19).

Consolidated controls built its first robot, originally called a " Universal helper" and then named "unimate" by Engelberger and Devol in 1959. The first unimate was installed in General Motors plant in 1959 By 1961, the first production unimate was sold At first the robot was sold to load and unload machines. The first few robots sent to General Motors and to Doehler-Jarvis worked with heated die-casting machines (19).

Unimation Inc. was founded in 1962 when Pullman Corporation and Condec entered into a joint venture. The

first symposium was held in 1970 in Chicago. As the robot
revolution exploded in Japanease industry in 1972 it became
a turning point, and Japan became the first nation to form
a robot association, The Japan Industrial Robot
Association **(JIRA)**. Four years later, the United States
opened the doors of Robot Institute of America **(RIA)** in
Dearborn, Michigan. In 1977, the British Robot Association
(BRA) was formed **(19)**.

A 1977 meeting of the Robot Insititute of America
resulted in a Delphi forecast. Reported by Engelberger
president of Unimation Inc , there are number of desirable
attributes with which robot should be equipped.
Sensor-controlled movements of robots such as vision and
tactile sensings are desirable traits in robots.   The
participants agreed that simple vision rated heighest
priority for research and development in robotics   All
sensory capabilities were seen to be available before 1985.
A shift was seen in the middle and late 1980s to more
sophisticated computer control. With this sophistication,
robots would be capable of coordinate transformation and
sensory feedback control **(19)**.

The Dephi forecast also listed twenty robot attributes
which were predicted and became a reality by 1984.   These
attributes are

1.   Work space command with six infinitely-controllable
     articulations between   the   robot   base   and a hand

extremity.

2. Fast, hands-on instinctive programming.

3. Local and library memory of any size desired.

4. Random program selection by external stimuli.

5. Positioning repeatability to 0.3 mm.

6. Weight handling capability to 150 Kilos.

7. Intermixed point-to-point and path-following control.

8. Synchronization with moving targets

9. Compatible computer interface.

10. High reliability.

11. Rudimentary   vision   via   orientation   data   or
    recognition data.

12. Tactile   sensing   via   orientation   data,   physical
    interaction data or recognition data.

13. Multiple-appendage hand to hand coordination.

14. Computer directed appendage tragectories

15. Mobility.

16. Minimized spatial instrusion.

17. Energy conserving musculature.

18. General purpose hands.

19. Man-robot voice communication.

20. Inherent safety.

Joseph   Engelberger,   founder of unimation Inc   was
named "The   father   of   robotics"   in   1983   by   American
Machinist   and   **RIA** for poineering   the   industrial   robot,
creating a new industry,   and providing a novel approach to
industrial automation **(19)**.

When RIA decided that there must be an agreed-upon definition of robotics, they cosulted with Engelberger and came up with this definition as "A robot is a reprogrammable multifunctional manipulator designed to move material, tools or specialized devices through variable programmed motions for the performance of a variety of tasks."

Where the key words in this definition are reprogrammable, multifunctional and manipulator (20).

Reprogrammable: The controller can be programmed for a completely new sequence of movements.

Multifunctional: This implies that the machine is more flexible than hardware automation, in that it can perform a variety of tasks.

Manipulator: This refers to the robot's ability to move an object through space, while at the same time re-orientating it's position

The British Robot Association (BRA) which was formed in 1977 has defined the industrial robot as "A reprogrammable device with a minimum of four degrees of freedom designed to both manipulate and transmit parts, tools or specialized manufacturing implements through variable programmed motions for the performance of the specific manufacturing tasks."

Japan's Industrial Robot Association (JIRA) and the Japanese Industrial Standard Committee (21, P.3) in the glossary of terms for industrial robots '(JIS B 0134-1979) defines the robot at various levels (21) as

Manipulator: A machine which has functions similar to those of the human upper limbs, and moves the object spatially, from one location to an other

Play back robot: A manipulator which is able to perform an operation by reading off the memorised information for an operating sequence, including position and the like, which it learned by being taken manually through the routine beforehand.

Intelligent robot: A robot which can determine it's own behaviour / conduct through it's functions of sense and recognition.

Today's industrial robots while varying in size, shape and performance, are generally composed of five main groups of components; manipulator, controller, power device including the power supply, teach padant or manual control either with or without monitors, and the auxiliary peripheral terminals (22). The robot manipulator consists of mechanical devices that do the work and provide the mastery of articulation, powered by pneumatic, hydraulic or electrical devices. Power amplifiers drive the axis motors, while the controllers accept the decoded software

information. The various modes of motion and their sequential points along the path are stored as programs in the memory, located usually in the robots custom-built computer. It is the controller that coordinates the motions about the manipulator axes and interacts via I/O devices with both internal and external sensors and synchronizes external machines, devices, conveyers or tools with which the robot carries out the work, test and inspection. Controllers vary in complexity, and may be as simple as logic circuitry or as sophisticated as 8 to 32 bit mini or microcomputer system (23).

1.6. ROBOTIC CONTROL

Robot control dominates the performance and utility of a robot. More efforts have been devoted to it in the past decades.

J.U. Korein and J. Ish-shalom have devoted framework for robot control according to the following three aspects (24).

(a)   Controller objectives.
(b)   System model.
(c)   Control methods.

The framework for robot control is illustrated in **figure 6.** This framework for robot control is helpful, to understand the context in which controllers were designed,

to understand the performance, which one can expect from each design and to classify all robot controllers.

To control and guide the joint motion in a robot, a drive system has basic importance. The speed, precision, and utility of robots depend on actuators and are the means by which they transmit power to their joints. The important criteria to evaluate actuators are (25)

(a) Dynamic range.

(b) Precision with which actuators may be controlled.

(c) Force or torque that the actuator can generate

(d) Size, mass, and cleanliness of the actuator.

The type of actuators for a robot could be electrical, hydraulic, pneumatic, or a combination of them. The combination of these three types of actuators is illustrated in **figure 7**.

1.7. CLASSIFICATION OF ROBOTS

The classification of robots can be done on the basis of (a) Trajectories based on motion control, (b) Structural configuration and most importantly (c) Performance characteristics of the robot, which requires higher level kinematics and kinetics considerations.

1.7.1. CLASSIFICATION OF ROBOTS BASED ON PATH CONTROL

There are two forms of robot path control   One is known as point-to-point (PTP) control and the other is continuous path control (2). With PTP control the robot is programmed to pause at each point to plan the next step in a predetermined manner   Despite the fact that motion is not controlled between the set points, it usually occurs along a natural path, depending upon the kinematic geometry of the robot   Automatic execution of the PTP program occurs with the block by block loading of the data into the working memory. The positions are recorded in rapid succession or traversed without stopping depending on the path functions. Most industrial robots produced today are operating in this manner. The use of additional memory in the control allows input and storage sequences of several moves in the CNC memory with program selection based on the part or process cycle (26). On the other hand the robot under continuous control can follow any arbitrary path accurately.

A PTP controlled robot offers greater precision in terms of accuracy and repeatability. This system of control is usually used in "pick and place" application. The continuous path control results in a smoother movement along the defined trajectory but there is a speed penalty, which is a function of the control usually performs functions such as fusion welding or spray painting while moving. The penalty

may be a 15% to 25% speed reduction, resulting in uneconomical control of the process, i.e. the efficiency will be lower compared with the same robot operating in point-to-point mode (21).

The performance of industrial robots with regard to range, slide path, speed, and precision depends mainly on the design details and differs widely from application to application (26). In robot control, a distinction may be made between two categories. The first category, described as the low level control, is for controlling the position and speed of the joint axes using the information from the internal sensing devices. This may involve the use of potentiometers, incremental or absolute shaft encoders attached directly or geared to the arm joint motor shaft The second category may be described as high level control which defines the functional motion. The computer, which obtains the data from both internal and external sensors, modifies this data according to the required kinematics and returns the modified data to the joint servos in order to control the position and speed, and to monitor the functional requirements for motion (21).

1.7.2. CLASSIFICATION OF ROBOT BASED ON STRUCTURAL CONFIGURATION AND ROBOT MOTION

This kind of classification is based on the

distinction between the three basic motions in relation to their operation. The first is the rotation about the longitudinal axis of a link between two joints which is called swivel motion. The second is also rotation about the transverse axis in the joint which is called bending motion. The third is linear motion in the direction along the longitudinal axis, either constructional or extension, which is the prismatic motion. According to the robot's joint movements, there are the following well distinguished basic configurations (21).

(I) Revolute or jointed robot

Revolute robot is the type which best simulates a human arm and is often referred to as an anthropomorphic robot. The revolute robot consists of three major rotary joints acting as the waist, the shoulder mounted on the waist, and the elbow mounted at the end of the shoulder link (21). An example is shown in **figure 8**. Typical examples are Asea (IRb-6, Sweden), and Unimation (Puma 550, 560, 760, U.S. and U.K.).

(II) Polar (Spherical) Robot

This robot rotates about the axis of it's waist on the base. The second axis is a horizontal rotary joint, allowing the arm to rotate in a vertical plane.

Making the use of both axes, the arm can sweep through a partial sphere. This mathematically corresponds to a polar coordinate system, thus this kind of robot is classified as polar. The third kind of freedom is provided by a prismatic joint built into the arm which allows it to move in and out (21). The robot can sweep through partial spheres of radii depending on the length of the prismatic joint. An example of this kind is shown in **figure 9.** Typical examples in this group are Unimation (Series 1000, 2000, 4000, U S.)and (GEC(little giant U.K.).

(III) Cylindrical Robot

This robot consists of a base, a horizontal arm and a prismatic joint built into the horizontal arm. The horizontal arm swivels around the vertical column, describing the partial cylinder in space. The prismatic joint built into the horizontal arm can slide in and out, remaining parallel to the base **Figure 10** shows an example of this kind of robot Typical examples are Paterson (Wiper 2500, 3000, U.K.) and Fanuc (M-M1, M-M2, M-M3, Japan.)

(IV) Cartesian (rectangular) robot sliding and gantry type

There are three perpendicular transversing axes by an up / down, a left / right, and a forward /

backward moving prismatic joint This mathematically corresponds to a cartesian coordinate system, thus this kind of robots are classified as cartesian. Despite the fact that the robots are of high precision, they are not preferred for many applications because of their difficult adaptability to the existing human operated work stations. **Figure 11 and 12** show an example of sliding and gantry cartesian robots, and typical examples are model program A3000, Italy and IBM (7565, U.S.) respectively.

(V) SCARA type robot

The Selective Compliance Assembly Robot Arm **(SCARA)** configuration has vertical major axes rotations for which the gravitional load, Coriolis and centrifugal forces do not stress the structures as much as they would if the axes were horizontal. In this kind of robot the new robotic configurations are obtained by combining the properties of the basic representatives defined in the first four kinds. For example, if Revolute and Cylindrical robot kinematics are combined, the result will be new type of robot called SCARA. **Figure 13** shows an example of SCARA type of robot. Other typical examples are IBM (7535 and 7545, U.S.) and Meta Machine (adept ones, U.K.).

1.8. APPLICATIONS OF ROBOTS

Due to lower costs and high reliability, advanced technology robots can be considered for more applications than before. Robots have had the advantage of operation in hostile environment, of being consistent and accurate, being more flexible, and cheaper than an equivalent dedicated palletiser (20).

Industrial robots have been used in a wide range of applications. The main application of robots has been in in material handling, arc welding, spary coating, assembly inspection, and even military and security purposes. **Figure 14** illustrates the range of robot applications.

1.9. NON-TRADITIONAL METHODS OF MACHINING

Non-traditional metal removal refers to processes, that do not develop the conventional chip. These processes used to be called "chipless machining" These processes were largely developed and used by the aerospace industries, but are now prevalent in the auto and appliance industries and in tool and die work. There are more than 30 newer processes (27) that can be broadly divided into four main classifications (27 to 30) based on the appearance of energy.

(i)   **MECHANICAL:** Ultrasonic Machining (USM), Water Jet

        Machining (WJM) and Abrasive Jet Machining (AJM).

(ii)   **CHEMICAL:** Photo-Chemical Machining (PCM)

(iii)   **ELECTRO-CHEMICAL:**   Electro-Chemical Machining (ECM)

        (ECM), Wire ECM , Electro-Chemical Grinding (ECG)

(iv)   **ELECTRO-THERMAL:** Electron Beam Machining (EBM), Ion

        Beam Machining (IBM), Plasma Beam Machining (PBM),

        Laser Beam Machining (LBM), and Electric Discharge

        Machining (EDM).

In **USM** (sometimes called impact grinding) a high
frequency generator (20 to 100 KHz; 0.1 to 40 KW) is
applied to a magnetostrictive or piezoeletric transducer to
obtain a mechanical vibration at the same frequency. The
tool is attached to a concentrator applied to enhance the
energy density. A slurry with abrasive particles is fed
between tool and workpiece. The tool materials are usually
brass, carbide, mild steel or tool steel. Concentration,
grain size and hardness of the abrasive slurry effect stock
removal, surface roughness and surface quality **(31)**.
Other crucial parameters are the frequency and amplitude.

WJM uses a high-velocity fluid jet impinging the
workpiece, performing a slitting operation. A long chain
polymer may be added to the water of the jet to make the
jet coherent (i.e. not to come out of the nozzle as a

mist) under 10,000 to 60,000 psi nozzle pressure. Alternative fluids (alcohol, glycerine, cooking oil) have been used in processing meats, baked goods, and frozen foods. The jet is typically 0.0762 to 0.508 m.m. in diameter and exits the orifice at velocities upto 914 m/sec **(29)**. Recently, a full range of ferrous and non-ferrous metals have been machined. The majority of the metal working applications require the addition of an abrasive to the water jet stream.

In **AJM**, the workpiece material is removed by the mechanical impact of a high velocity air jet with abrasive particles. **AJM** is a rather slow process (. 10 mg/min ..); however, it is quiet cheap, forces on the workpiece are limited and no thermal problems occur because of the cooling effect of the expanding air. Most often, aluminium oxide or silicon carbide powders are used as abrasive media **(28)**. Nozzles are made of tungston carbide or synthetic saphire with circular openings from 0.15 to 2 mm. diameter. The main parameters influencing the material removal rate and surface quality are air pressure, size of abrasive particles (... 60 micro-meters ...), spray angle tool to work distance (2 to 15 mm.) and feed rate (0 to 2 mm/sec.) **(32)**.

The material removal in Chemical Machining **(CHM)** is based on a chemical reaction between workpiece and etching fluid. On areas where a mask covers the surface, no

chemical reaction and thus no material removal occurs. The process is used for the removal of thin layers (max. a few mm.) **(28)**.

In **ECM**, direct current, at high amperage and low voltage is passed through a narrow gap between a shaped electrode and a conductive workpiece. Since the voltage is not sufficient to create an arc across this small opening, an electrolyte is passed through the gap. The electrolyte is usually a chemical salt or mixture of chemical salts usually NaCl, KCl or other additives disolved in water. This electrolyte is kept circulating through or around the tool. **Figure 15** shows a schematic drawing of the **ECM** process. As the current passes from the workpiece to the electrolyte, particles on the surface of the workpiece are dissolved by the electro-chemical reaction and hydrogen gas is produced at the electrode **(33)** Dissolved material, hydrogen gas, and heat are carried away from the workpiece gap (0.762 to 0.0762 mm., with 0.254 typically) by the electrolyte flow (50 to 200 feet/sec). The shape produced in the workpiece is nearly the mirror image of the electrode. The rate of machining is dependent upon the current, the time duration for which current passes, relative atomic mass of the metal, and valency of the ions produced **(30)**. The feed rate corresponding to the material removal rate ranges between 0.5 to 10 mm/min, when applying a current density of 10 to 1000 A / Cm square **(28)** ECM is implemented for mass production of small high-precision components (accuracy better than 10 microns) **(34)**. ECM has

the few distinct advantages over EDM, like, no electrode wear, high material removal rates, and the absence of process-induced residual stress or thermally altered workpiece surfaces (33). The major problem in ECM is "over cut" i.e.; the undesired and uncontrolled electro-chemical over disolving of the workpiece (28).

In **ECG** the workpiece is the positive electrode (the anode), and an electrically conductive abrasive wheel is the negative electrode (the cathode). The two electrodes, wheel and workpiece, are essentially touching. The result is that current densities (Amperes per square inch of contact between electrodes) can reach as high as 3000 amps/inch^2. As the electric current flows between the workpiece and the wheel, through the electrolyte, a chemical action occurs on the workpiece that causes the surface metal to change to a metal oxide. This soft surface metal oxide is wiped away by the abrasive in the wheel (35).

Laser Beam Machining **(LBM)**, which is based on conversion of electrical energy into light and then into thermal energy, emits an intense, coherent, highly collimated beam of single wave length light which, when focused by an optical lens, produces a small intense spot of light on the workpiece surface (34). High power densities up to a million W/mm square can be acheived (28). **Figure 16** shows a schematic diagram of LBM. The beam can be focused down to 0.127 mm in diameter for drilling

micro-holes through metals as thick as 2.54 mm., but hole depth-to-diameter ratios of 10:1 are more typical (29). Lasers are classified by their lasing medium: solid state, liquid state, or gas. They work best in thin materials or non-metals. Laser has the potential for being very short period of time, 0.508 mm hole can be drilled through 2 5 mm thick supper alloy in one to three seconds (36).

1.10. ELECTRICAL DISCHARGE MACHINING (EDM) --- A REVIEW

EDM, sometimes referred to as spark erosion machining, which stands in the group of electro-thermal machining process (37 to 40), has the most practical advantages and is the one most widely used in manufacturing engineering of all the non-traditional methods of machining (41).

EDM is the method of removing metal by a series of rapidly recurring electrical discharges between an electrode (cutting tool) and the workpiece in the presence of a dielectric fluid. Minute particles of metal or chips, generally in the form of hollow spheres, are removed by melting and vaporization, and are washed from the gap by the dielectric fluid which is continuously flushed between the tool and workpiece (42,43). Figure 17 shows an EDM die sinking process.

The workpiece which constitutes one of the electrodes between which sparks occur, must be an electrically

conductive material. The other electrode (tool), which also must be made of an electrically conductive material is located in close proximity to, but not in contact with, the workpiece during cutting (42,44). There is no mechanical force involved during EDM process (45 to 48) between cutting tool (mostly anode) and workpiece (mostly cathode) (28), so hardness of material does not effect (49) machining process, but it's polarity, thermal conductivity and melting points are the governing factors in the process (30,50).

The phenomenon of the electric spark has been known for 200 years (51). EDM began in 1940's, when Russian inventor Boris Lazarenko and his wife began a systematic study of contact erosion in electrical switches. These inventors discovered that different contact materials eroded under arcing at different rates. Later, four Swiss inventors spent several years in a garage working on the embryonic technology. In 1954 the Swiss founded the Agie Corp., which developed wire cut EDM. This method was introduced to the US in 1969 (52) In 1950's the Resistor Capacitor tube type generators were used in the industry to create shapes in hardened steel. In 1960 pulse generators were created along with solid state generators to greatly reduce electrode wear to less than 1% . In the 1970's, orbiting systems were invented to reduce the number of the electrodes used to create a cavity (53). In early 1960's, the art of numerical control came to EDM. Computer

Numerical Control (CNC) entered the scene in the early 1970's, taking root first in Europe and Japan (52). CNC EDM was introduced in the US in 1980's.

There are more than 30 variables in the EDM process and the relationship among the variables and parameters is rather complicated (54). Each discharge dissipates, within a very short period of time, an amount of energy (0.4 mJ to 12 J) on a very localized spot on the workpiece surface (55,56). Due to a very high concentration of power (100 to 10000 KW / mm. square) a minute volume of material may be removed by melting and evaporation (28,37,38) The distance between the surface of the electrode and the surface of the workpiece represents the overcut and is equal to the length of the spark, which is essentially constant all over the areas of the electrode, regardless of the size or shape. Figure 18 shows a schematic diagram of EDM process and an overcut. A part of the total energy is also absorbed by the tool electrode; hence some tool wear occurs as well. This tool wear can be reduced to 1% or less of the material removal with an adequate selection of tool and workpiece material and appropriate generator settings (37,38,57). With classical die sinking machines, surface roughness of Ra = 0.1 to 0.2 micro-meters have been acheived (56). The tool electrode materials usually in use are graphite, copper, copper graphite, brass, zinc alloys, steel, copper tungston, silver tungston and tungston (machine data hand book). The generator power supply can be controlled through a computer. The power

supply has it's own memory station. In this case, the values can be preset like the time duration, voltage, amperage and polarity and lock it into number one memory station. There are a number of seperate memory stations to lock in sets of machining conditions from roughest condition to the finest finish **(53)**.

There are various types of generators in use. However regardless of the type, they should all meet four essential requirements **(58)**.

(i)   An adequate voltage supply to initiate and maintain the discharge process.

(ii)   Means of adjusting the intensity of the discharge current.

(iii) A means of adjusting the duration of the discharge.

(vi)   A means of controlling the cycle rhythm of the discharges.

For generating discharge the RC (Relaxation Circuit or Lazarenko circuit) was the first to be used. The circuit **(See figure 19)** comprises a DC source that charges a capacitor across a resistance The capacitor, connected to the tool electrode and the workpiece, discharges current across the spark gap when the continuously increasing capacitor voltage reaches the ionization voltage of the dielectric. After the discharge the dielectric deionizes, the capacitor recharges and the cycle repeats. The fundamental advantages of RC are their comparative

cheapness, simplicity of design and their relative extensive range of discharge energies (58). However, in spite of the many modifications to RC they are still subject to high tool wear and slow machining speeds compared to other types of generators. The independence of certain parameters i.e; discharge intensity, duration and energy values, creates a certain degree of inflexibility.

The introduction of semiconductors has improved the design of pulse generators and allows the frequency and energy of discharge to be varied with a greater degree of control. An arrangement incorporating feedback is shown in **figure 20**. In this circuit the conditons at the spark gap are monitored by a detector unit which determines the exact moment of current flow after the ignition lag. The time base for the off period ensures a constant interval for de-ionization and for the flushing away of the debris by the dielectric. Consistency in the energy of the discharge as shown in **figure 21** results in a much more efficient operation.

The pulse parameters voltage, current, and time can be set on the generator. Their actual value is a function of the type of application and situates as follows: current value (1 to 150 A) open circuit voltage (80 to 250 V), pulse duration (1 to 3000 micro-Sec.), pulse interval time (1 to 3000 micro-Sec.) (37,38,55) and pulse frequency upto 3000 KHz. A tool feed system is necessary in order to maintain the required voltage gradient in the working gap

as well as to avoid short circuits. Therefore a servo system controls and adjusts the gap width **(38,56)**. The metal is always removed in a direction normal to the surface irrespective of the shape of the tool electrode and in the direction of it's advance. This is due to the fact that the current takes the path of least resistance between the workpiece and the tool electrode **(59)**. Heating effects normally do not cause any metallurgical change to the **EDM** Machined surface to a depth greater than 0.05 mm. Low spark energy cuts are even possible that show little or no metallurgical surface change **(47)**.

The flushing is not used during actual eroding, only when the electrode is withdrawn by the timer, eroded area is flushed strongly (2-3 atmosphere pressure). As soon as the electrode starts to re-engage with the work, the flushing is stopped. If flushing is continued during **EDM** process, the metal particles which are transported upwards in the stream of gas bubbles will only be forced downwards again by the flushing action, thus increasing the danger of arcing **(60)**.

The **EDM** process is usually carried out in the presence of a dielectric fluid. A dielectric fluid must meet three requirements to insure the superior performance and economical operation of an **EDM** machine. Firstly, it must insulate until the required conditions are acheived between the electrode and workpiece, it must then be a conductor. Secondly, it must cool the workpiece electrode

and machined particles. Finally and most importantly it must flush the particles out of the spark gap (58,61). Dielectrics that meet these requirements have some very specific characteristics, such as: low viscosity, high dielectric strength, high flush point, freedom from acid alkali and acid corrosive sulphur, resistance to oxidation and sludging, low pour point, compatability with materials used in EDM construction, and low toxicity to machine operators. A dielectric with superior qualities in these areas can make the difference between a successful EDM operation and a mediocre operation. The common dielectrics in use are kerosine, deodourized kerosine, diesel fuel, deionized water, paraffin, white spirit and light transfer oils including similar materials.

Electronic control of the spark assures that the spark energy is very predictable, very controllable, and very repeatable (47). Adaptive Control (AC) of machining processes is applied to improve the overall efficiency and reliability of the process (62). EDM machine manufacturers succeeded in technological innovations in electromechanics (high accuracies, high efficiency machining by transistorisation, numerical control and adaptive control), thereby achieving automation and functional expansion (63). Adaptive Control is specially suited for EDM in view of the following (38,39,40,56,62,64).

(i)   **EDM** is a slow material removal process, automation may reduce machining time, but it might be especially interesting in terms of an increase in machine autonomy.

(ii)   Advanced electronics facilitates process control performance, since most of the control signals can be electrically detected.

(iii)   Low cost electronics hardware relative to the cost of **ED** machines enables the application of control techniques. It might yield an optimization in terms of tool wear or removal rate.

(iV)   The stand alone capability of the machine is improved and machine costs are reduced due to less intensive manual control and shortage of skilled manpower.

The introduction of AC and optimization techniques in **EDM** **(27,28)**, together with numerical control features, yields an increased process efficiency and allows enhanced unmanned machining (up to 48 hours and more). The computer in **CNC EDM** allows the machine tool to position, to machine to orbit, to flush, to change parameters or even to change electrodes **(63)**. **CNC** simplifies many of time comsuming aspects of EDM operation by setting and remembering zero points, eroding complex shapes with simple electrodes, measuring and compensating for electrode

wear, and by solving many complex setup jobs drilling
micro-holes through metals as thick as 2.54 mm

In recent die sinking **EDM** machines, the following
improvement made possible by **NC** throughout the machine

(1)   A planetary motion is induced between the electrodes
and the workpiece to increase accuracy and removal
rates. ' Moreover the number of electrodes required
for achieving the necessary accuracy is reduced and
safety against fire which might be caused during
machining is increased. More uniform distribution of
wear **(66)**. It increases the flexibility of the shape
to be generated **(67)**

(11)   Appropriate steels with a small area of 10 cm² or
less can be machined to a mirror like surface.

(111) Machining to a complicated shape is possible by
expressing it as an assembly of simple shapes and
using **NC** automatic tool changer with a large number
of programmed simple shape electrodes.

(1v)   Numerical Contouring control **(NCC)** EDM enables us to
perform high speed and low energy **EDM (68)** because by
the profile electrode we leave the stock to be
removed as a solid material

(v)   In the **NCC-EDM** by standardizing the electrode shape, machining accuracy, repeatability and resistance against electrode wear can be improved **(68)**.

(vi)   With a fine grained graphite tool, it is possible to drill holes of 0.4 mm diameter to a depth of 150 mm. Indeed, holes as small as 0.05 mm are possible through very limited depth **(60)**. Burr free holes of 0.039 inches through heat treated tool steel with a small radius, convex surface, in a precise and repeatable location became possible **(69)**.

EDM has it's own application areas mainly in diemaking **(38)**. Ideal die material requires both the hardness of diamond and fracture resistance of hard metals. Cemented tungston carbide, and syndite (polycrystalline diamond) are some of the materials which approach this ideal. Machining such hard materials can be done by using laser or **EDM** process. Holes produced by laser generally have some taper because the beam is focused in one plane, and laser generated holes are not as precise in geometry (diamond smoothness, surface finish) as **EDM** generated holes One possible alternative is to laser cut a rough die profile by varying the angle of the die, tilt, rotation speed, focal point, pulse frequency, and then finish the die profile to close tolerance with a short, finish **EDM** cut **(70 to 75)**.

1.10.1. PHYSICAL BASIS OF EDM

The erosion mechanism is attributed to the electical breakdown of the dielectric in the inter electrode gap caused by the application of voltage pulses, see **figure 22.** The breakdown arises from accleration towards the anode of both the electrons emitted from the cathode by the applied field and the stray electrons in the gap. These electrons collide with neutral atoms of the dielectric, thereby creating positive ions and further electrons, which in turn are accelerated towards cathode and anode respectively. If multiplication of electrons by this process is sufficiently high, an avalanche of electrons and positive ions occurs. These eventually reach the electrodes and the current flows The entire breakdown process is a localized event, occuring in a channel of radius approximately 10 microns **(42,76).** When the electrons and positive ions reach the cathode anode, they give up their kinetic energy in the form of heat (8000 to 12000 degrees celsius) **(30,59)** A large level of heat flux can be attained, so that even with sparks of very short duration (of the order of micro-seconds) the temperature of the electrodes can be raised locally to more than their normal boiling point Owing to the evaporation of dielectric, the pressure in the plasma channel rises rapidly to values as high as 20 atm **(76,77).**

Such great pressures prevent the evaporation of the super heated metal. However, at the end of the voltage pulse, when the voltage is removed, the pressure also drops suddenly and the super heated metal evaporates explosively. Metal is thus removed from the electrodes.

1.10.2. WIRE ELECTRO- DISCHARGE MACHINING (WEDM)

In Wire Electric Discharge Machining (WEDM) cutting metal is eroded away by electric discharges between the workpiece and a thin wire electrode, with no tool workpiece contact and without the application of mechanical forces (46). The wire electrode runs through the workpiece like band saw blade, except the wire is used only once (78,79), and is surrounded by a stream of usually deionised water which serves as conductor for the current as well as coolant and means of removing the machined metallic particles (36). The wire is continuously renewed in order to compensate the diminution of the wire diameter by the spark erosion process (80). The cutting wire is capable of cutting pre-hardened steel to finished die dimensions (81). Figure 23 shows a schematic diagram of equipment for electrodischarge machining using the moving wire electrode.

A wire diameter of between 0.03 and 0.3 mm is normally used, with 12 intermediate diameters (46). EDM eliminates most of the hard tooling that would be required for conventional machining, and it has the low tooling costs (79). The wire erosion process provides the important advantage that punches, dies, and strippers can be cut from hardened steel blanks in single block and operation (82,83). WEDMs have been used in industry since 1969 (84) and have been numerically controlled since their initial developments (85).

In WEDM, the distance from wire to workpiece is usually around 0.025 mm. In this tiny space, metal is being eroded by rather violent but extremely localized and momentary action, a "thunder storm in a slot" (78). The criteria of quality are the surface roughness and tolerance. The roughness standards range from finish to fine finishing quality (Ra 2. ..0.2 microns and Rz 10 . ..1.5 microns), the latter values being comparable with the results of polishing and lapping (46). Shape accuracy in WEDM in a working environment with temperature variations of about 3 degrees celcius, can be about 4 micro-meters. If temperature control assures +/- 1 degree celcius, the accuracy obtained is about 1 micro-meter (63), and inner corner radii of 20 micro-meters can now be obtained (56).

One of the most important constraints in **WEDM** cutting is the occurance of wire rupture **(86,87)**. The possible solution to the wire rupture problem may be given by the application of ACO system **(88,89)**.

Tanimura and Heuvelman **(90)** pointed out that wire breaking was usually related to the rate of the short circuit pulses during the period of 30 m Sec. or more, which usually preceeds a rupture of the wire electrode.

Kinoshita, Fukui and Gamo **(86)** stated that wire rupture can be avoided by monitoring the pulse frequency. These authors observed a drastic increase of this frequency just before the breaking phenomenon during 5 to 40 m Sec. They (authors) also pointed out three main reasons for wire rupture.

(i)   If the wire is thin, the working gap is stable, and the working current is increased according to the rise of pulse frequency.

(ii)   Because of the poor design of the wire winding system, especially in take up reel.

(iii)   Wire breakage is closely related to the time concentration of discharge pulses.

If the workpiece feed rate is selected at low level, both breaking and short circuiting never occurs as long as the electrode wire travels (86). Appropriate flushing conditions during the erosion process are important to avoid wire rupture (87). In WEDM there are two systems of flushing in general use. In the first system, jets of water arranged in a co-axial manner with the wire, are injected into the gap from top and bottom. In the second system, whole area of erosion is submerged, and ocasionally supplementary flushing is applied. Neither system as yet has shown any marked advantages over the other, and it is therefore principally a matter of accepting the system incorporated in the choosen machine tool.

In **WEDM**, the electrical energy that must be supplied is small compared with that of EDM sinking performance, since most of the control signals can be Hence, **WEDM** produces a very small heat affected zone, so the removal of 0.008 to 0.013 mm from the surface restores the properties of the parent material to the surface (36). Steel develops a soft layer of about 10 microns thick on the surface (63).

In the 1960's, machining rates were typically 20 mm²/ minute (i.e., feed speed in mm/min. x workpiece thickness in mm). In 1984, machining rates improved to 200 mm²/ minute with accuracies of +/- 5 microns and inclination angles up to 12 degrees (63,65). In 1979

the possible maximum taper angle obtained was 5 degrees (92). Recently tapering of workpiece up to 30 degrees for 12 mm thick workpiece having surface quality Ra = 0.4 microns is fully integrated (28,93). Rough cutting rates for die steel are 260 mm²/min. (70 mm thick), finish cut for die steel 130 mm²/min., for carbide, half the cutting rates of die steel, and two and half times more for the aluminium.

The increased automation in WEDM is largely due to various developments, such as automatic wire insertion, restarting of the process in case of wire rupture, integrated start hole drilling and integration of ACO strategies to avoid wire rupture (94). Stand alone machining time up to 72 hours now become possible.

1.11. PLAN AND AIM OF THE PRESENT WORK

Since the introduction of numerical control, and the appearance of microprocessor based computers, the revolutionary changes have occured in the field of manufacturing engineering during last three decades. Furthermore, the other extensions in the field control optimization of different processes have opened the door for more research in these developing technologies

The literature for the present research project in the previous sections describe the following areas in general:

1)   The evalution, development and historical background of NC system.

2)   Development of NC to CNC and DNC, and incorporation of adaptive control.

3)   Evalution and development on robots including classification and applications.

4)   A brief introduction of non-traditional methods of machining, and a detailed review of the EDM process in particular.

The aim of present research work is to build a prototype manipulator, that can be controlled by micro-computer based software, to generate 2-D and 3-dimentional complex shapes for internal as well as external machining. The manipulator can be used on any existing WEDM, ECM, or LBM machines in which mechanical forces are relatively negligible, and at the same time it should offer more angular cutting flexibility than any of the existing totally integrated and expensive WEDM machine can offer.

The objectives of the present project are

1) To design and fabricate a prototype precision manipulator for external and internal machining facilities which will be suitable for existing WEDM machines.

2) To interface the manipulator to a micro-computer

3) To commission the manipulator in conjunction with hot-wire and model material.

4) To develop software to demonstrate the actual capability of the manipulator/software for different motions to generate 2 and 3 dimensional complex shapes.

5) To simulate WEDM tests using model material and model machining facility

6) To check the accuracy and repeatibility of the geometries generated for different speeds of operation and different geometries.

The contents of this thesis are divided into two volumes. The main text of the six chapters, references and bibliography is given in volume one. The appendices belong to chapter two, three, four and papers published are given in volume two.

The main text of the volume I is sub-divided into six chapters. The first chapter is introduction, which contains the litrature survey of different aspects related to this research work, and the scope of the present work. Chapter two describes the design, material, equipment section and manufacturing of the manipulator. Chapter three explains the dedicated interfacing system of this research work. Chapter four explains all the software developed for different geometries and control part programes for the manipulator. Chapter five which is concerned with the results obtained from the software and generated shapes and includes the discussion of this research work. Chapter six presents the conclusion and suggestions for future work. Finally the references which are quoted in the text of the thesis and bibliography are listed after the main text.

The appendices contain the calculations related to chapter two, specifications and list of special commands related to the interfacing system which have been used in the developed software, listing of all software which have been developed for this research work and papers published from this research work are given in volume two.
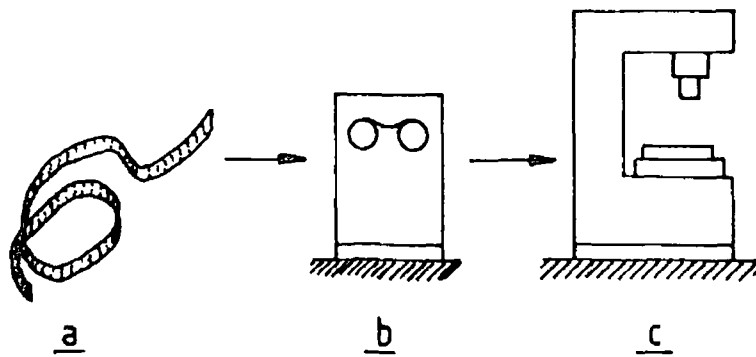
Figure 1. Three components of Numerical Control (NC)
(a) program of instructions (b) controller
unit and (c)machine tool

Tape reader for initial program entry	Mini or micro computer (software functions and NC part program storage)	Computer hardware interface and servo-system	
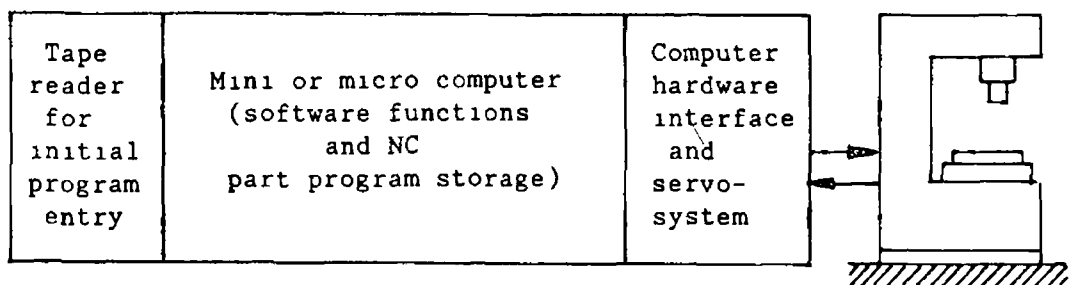
Figure 2. General configuration of Computer
Numerical Control (CNC) system

Telecommunication lines

Central Computer	Bulk memory NC programs

machine tools
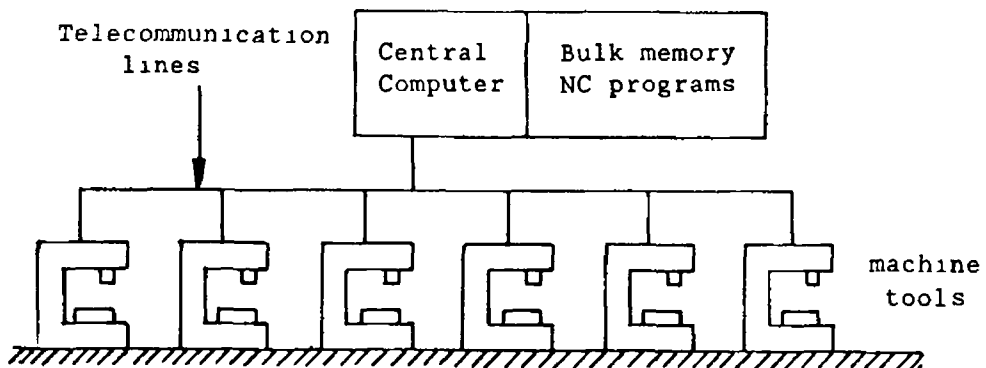
Figure 3. General configuration of Direct Numerical
Control (DNC) system
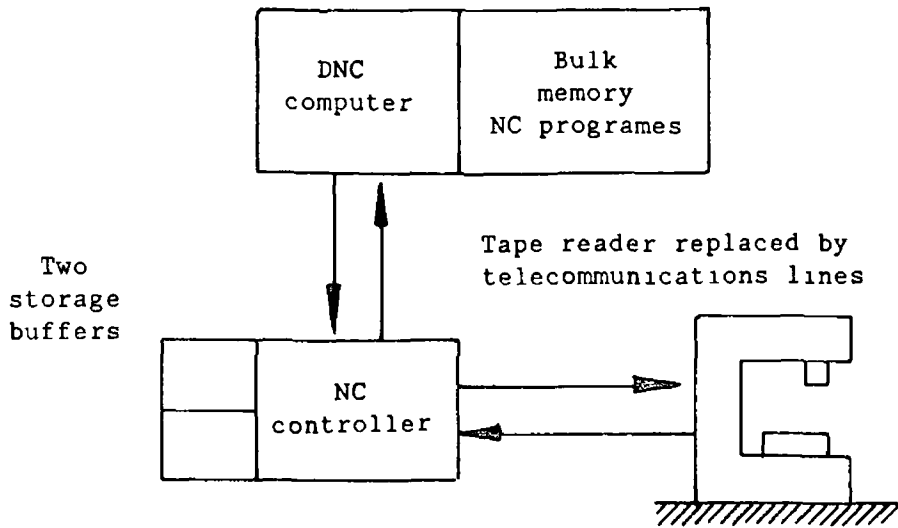
Figure 4. DNC with Behind-the-Tape Reader configuration
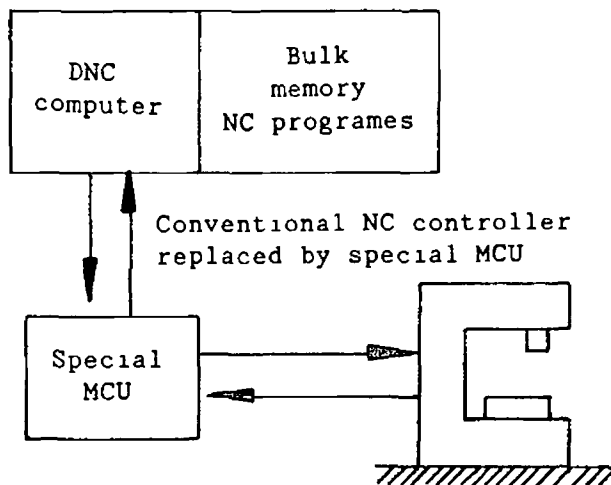
Figure 5. DNC with special Machine Control Unit (MCU)

robot control

control objetives

system control

control methods

| no interaction | weak interaction | strong interaction | extent | type | decompositions | open-loop | close-loop |

- get to point

- follow path to point

- accurate path following

- trajectory following

- improve trajectory following by learning

- local trajectory interpolation

- object approach

- collision avoidance

- applied force

- interface impedance

- control system language

- wobble

- uncertainty
  geometric
  dynamic
  induced

- robot itself
  kinematics
  dynamics
  structure
  actuators
  transmissions
  sensors

- robot interactions with environment

- failure

- static algebraic equations only

- dynamic and ordinary differential equations

- dynamic partial and ordinary differential equations

- finite element

- equation type
  algebraic

  ordinary differential equations

  partial differential equations

- clustering variables into independent groups

- nominal and perturbed

- time scale

- optimization scale

- information structure

- PID

- variable structure

- adaptive control

- frequency domain

- optimal control

- optimal decision strategy

- compliant control

- hybrid control

Figure 6. Framework for robot control

type features	electric	hydraulic	pneumatic
advantage	high accuracy high repeatibility less expensive easy to maintain easy to design clean	high speed higher power-to-weight ratio physical strength mechanical simplicity	quick assembly low operating and maintenance costs
disadvantage	lower power-to-weight ratio low speed low payload	noisy and dirty may suffer from oscillations and hydraulic hammer. additional maintenace and floor space	low accuracy low repeatability difficult position and speed control
available units	stepper motors, DC motors, optical encoders, etc	hydraulic servo valves analog resolver units	limited-sequence control bang-bang control

Figure 7. Shows comparision of actuators
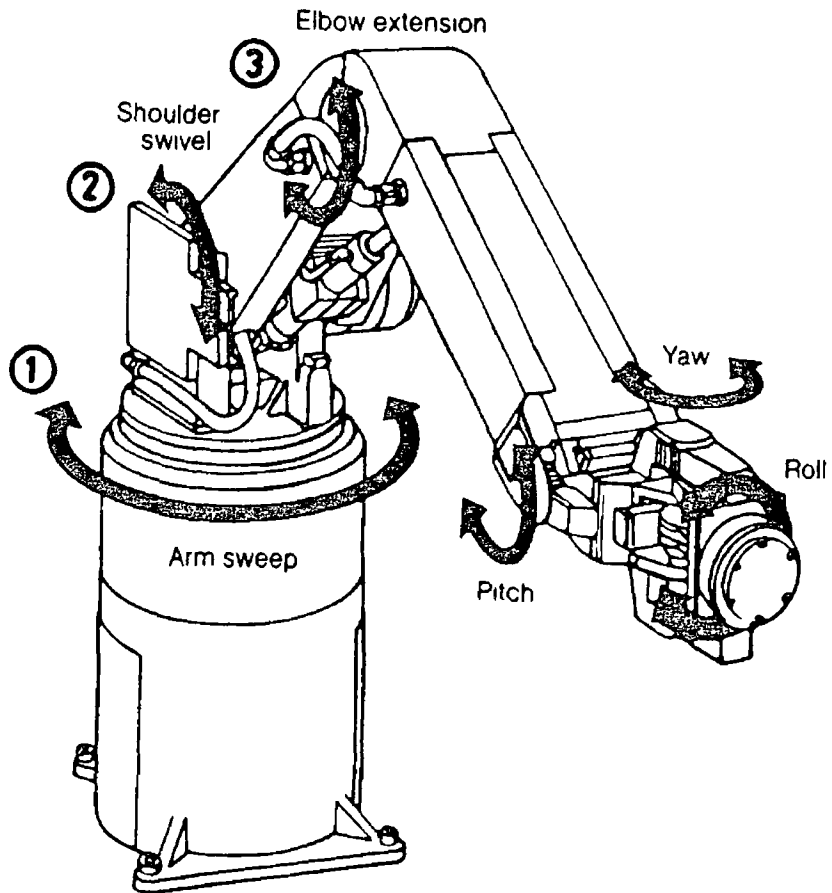
Figure 8. Shows the structural configuration and motion arrangment of revolute robot (Cincinnati Milacorn T3)

ROTARY MOTION
②

RADIAL MOTION
③

④
PITCH

⑥
ROLL

YAW ⑤

①
VERTICAL
POLAR
MOTION
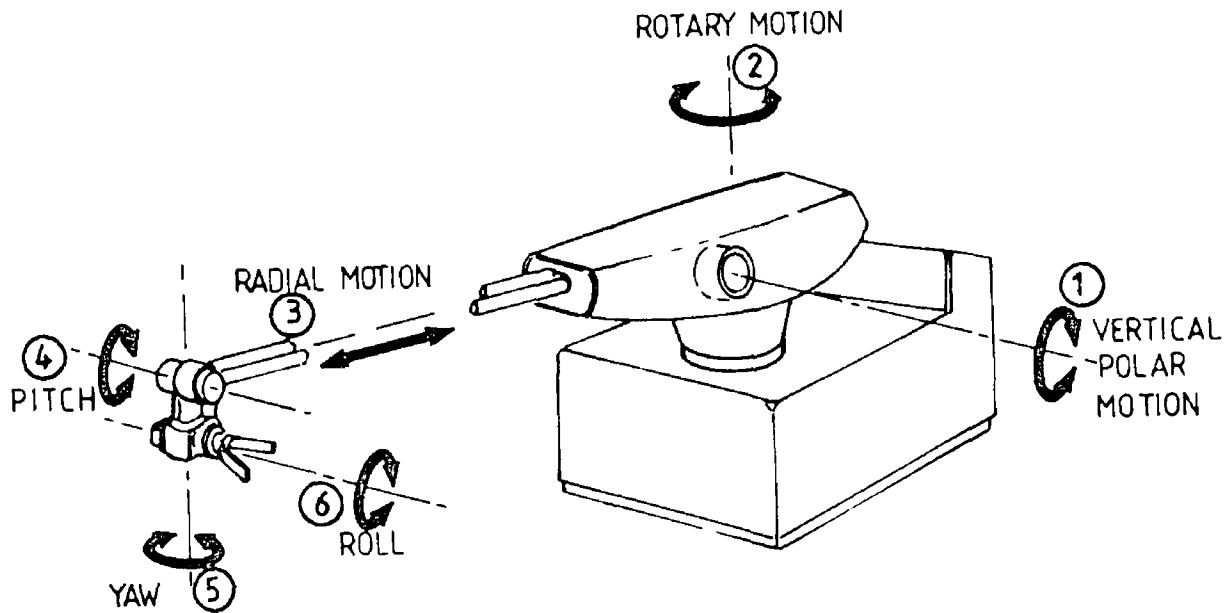
Figure 9. Shows Polar robot (Unimate 2000)
indicates the motion and structural
configuration
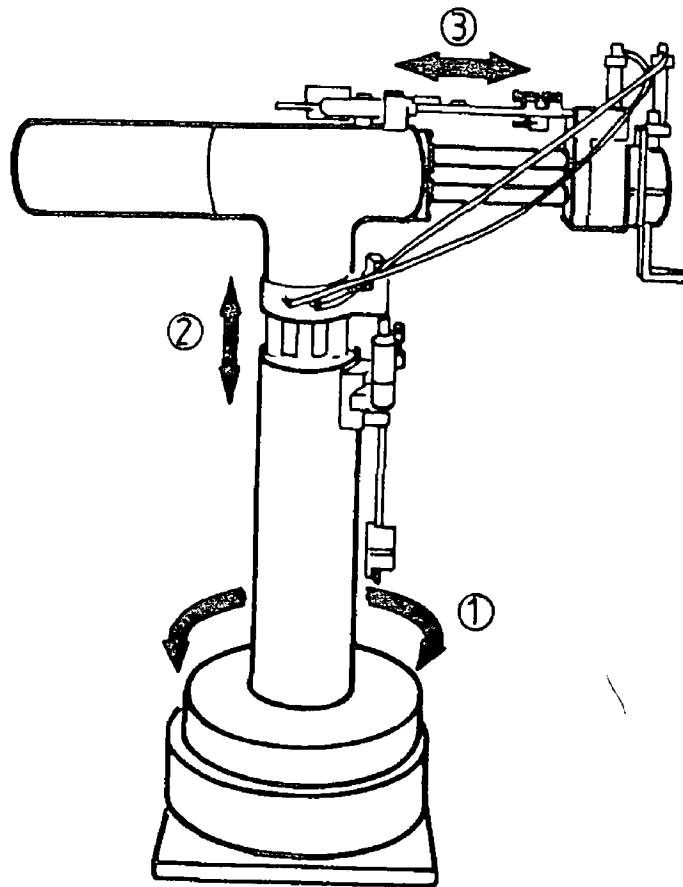
Figure 10. Shows cylindrical robot (Paterson Wiper 2500). This robot has two prismatic motions and one rotation about it's vertical axis
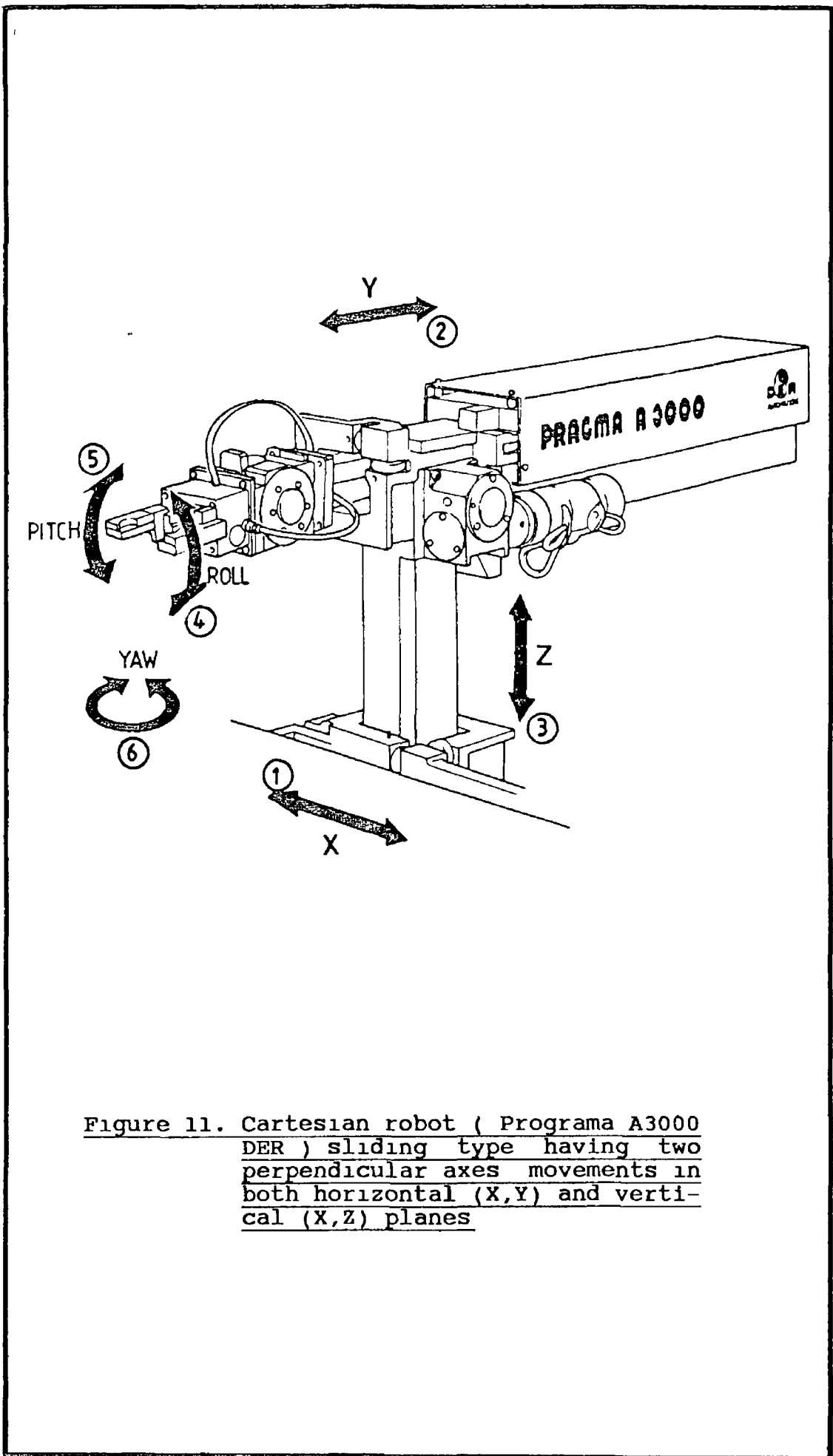
Figure 11. Cartesian robot (Programa A3000
DER) sliding type having two
perpendicular axes movements in
both horizontal (X,Y) and verti-
cal (X,Z) planes
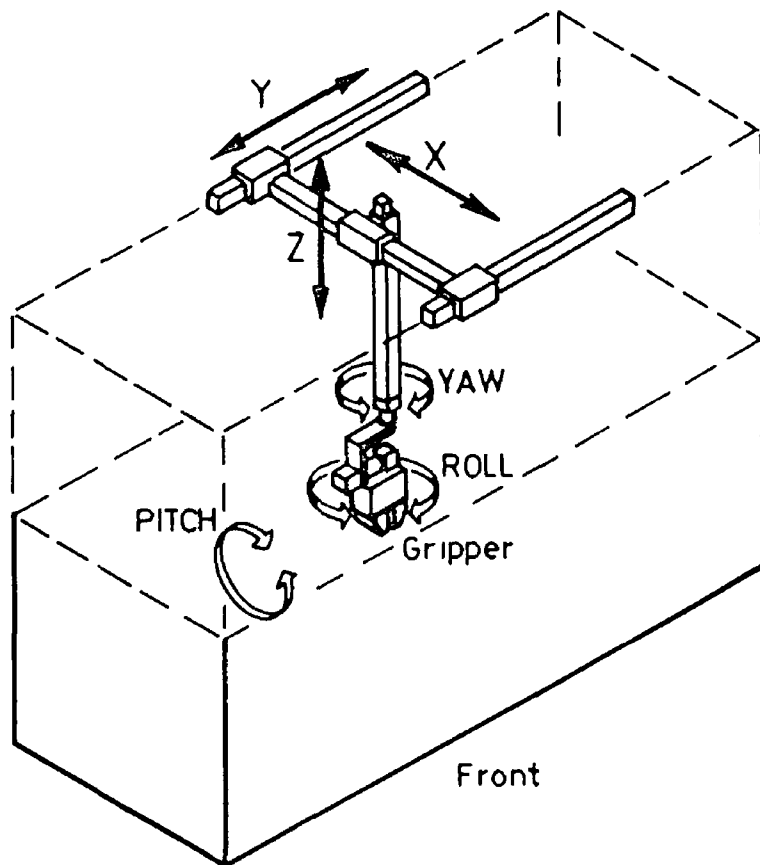
Figure 12. Cartesian coordinate robot (IBM 7564) Gantry type. Three translatory motions in X,Y, and Z directions. Three rotary motions
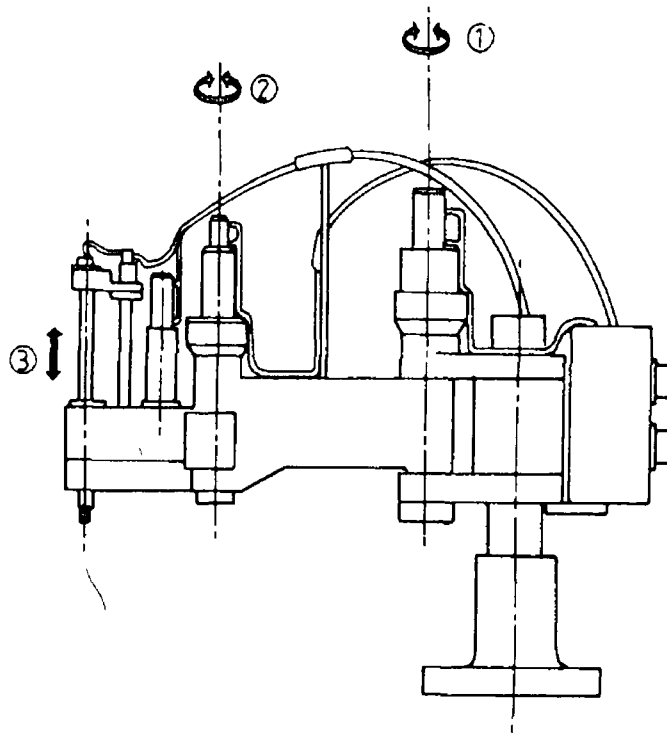
Figure 13. SCARA type robot (GEC A3020), the shoulder and elbow joints can rotate in the horizontal plane about their vertical axes. At the end of robot there is a vertical axix for lifting
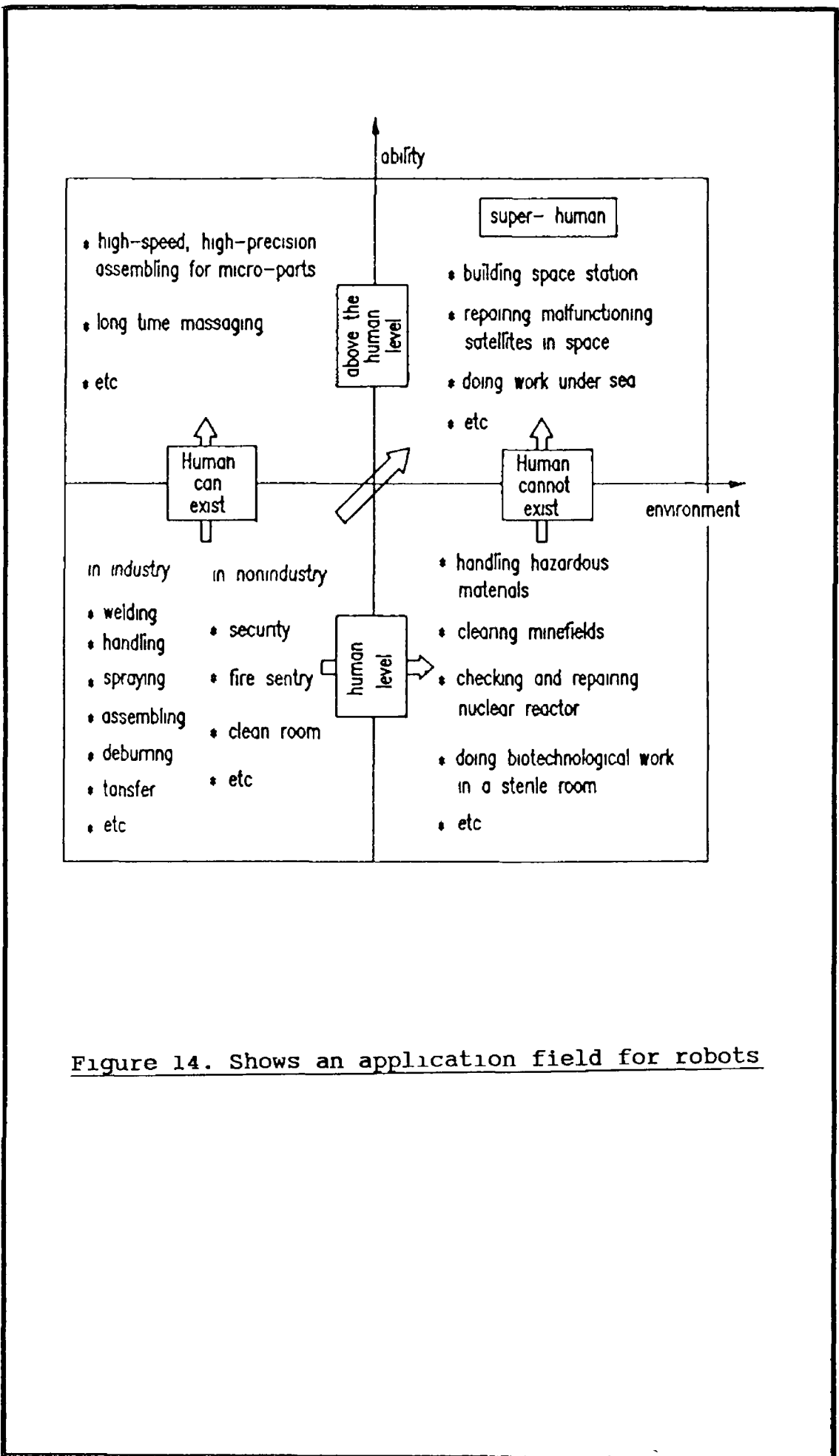
Figure 14. Shows an application field for robots
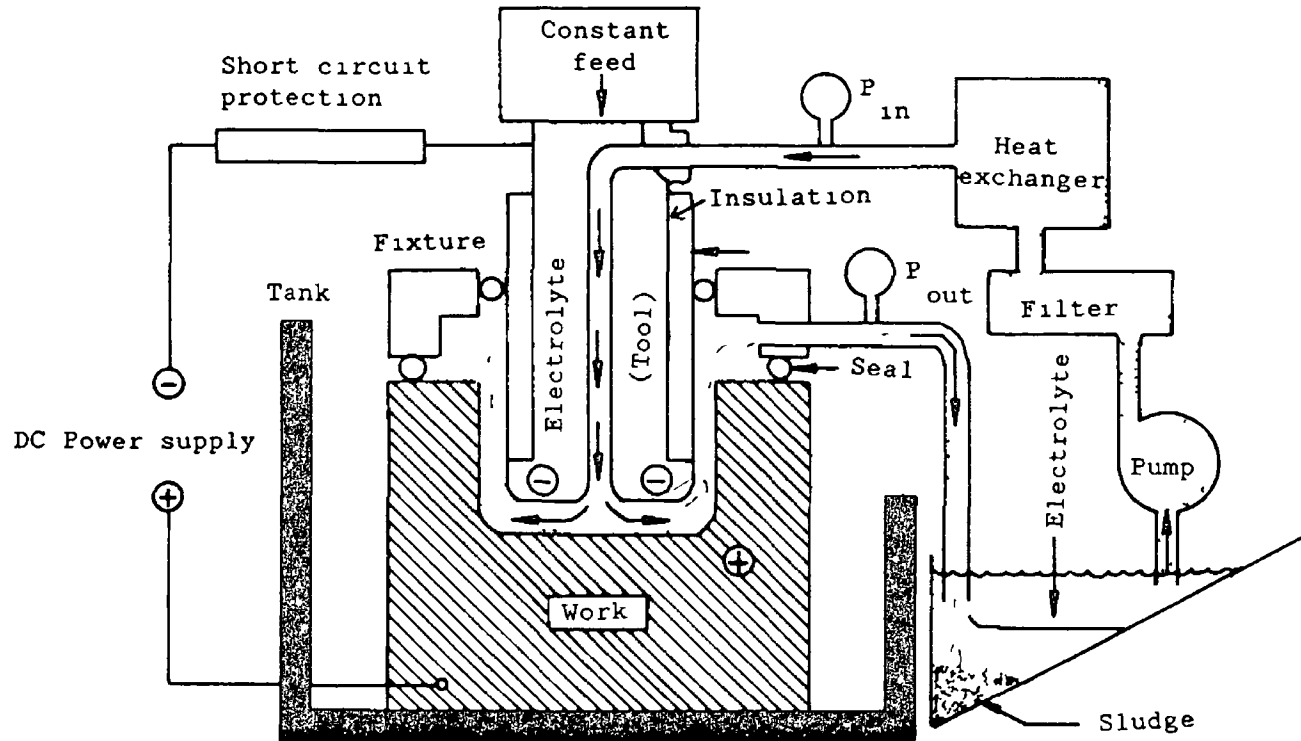
Figure 15. Shows a schematic diagram of an electro-
Chemical Machining (ECM) process
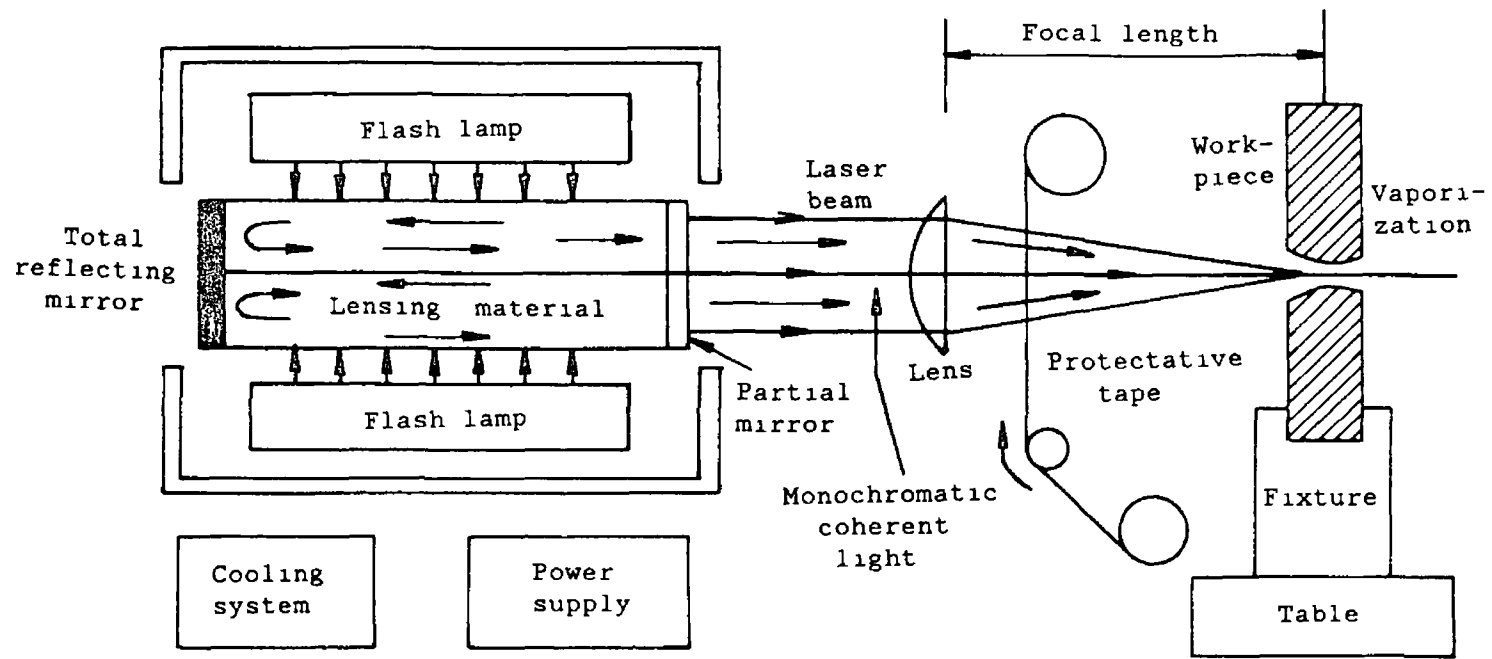
Figure 16. Shows a schematic diagram of a Laser Beam Machining (LBM) process

A. WORKPIECE.
B. DIE.
C. ELECTRODE.
D. DIELECTRIC.
E. ELECTRODE MOVEMENT.
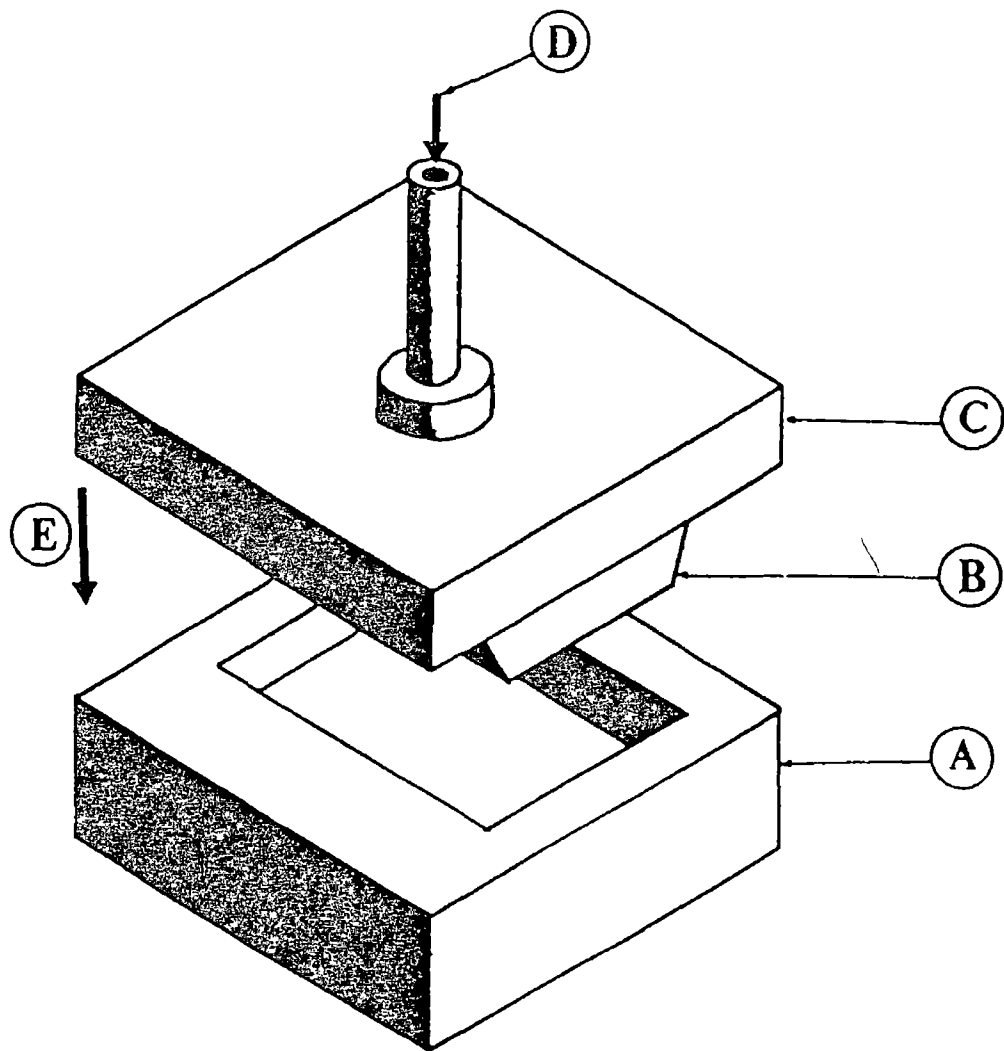
Figure 17.   EDM die sinking

Servo to
control
gap

Tool
feed

Over cut = Length of spark
(Spark discharge in gap)

Tool (anode)

Ionized
fluid

Dielectric

Filter

DC
Pulse
genra-
tor

Tool

Dielectric
fluid

Work

Fixture

Tank

Pump

Workpiece (cathode)

Table
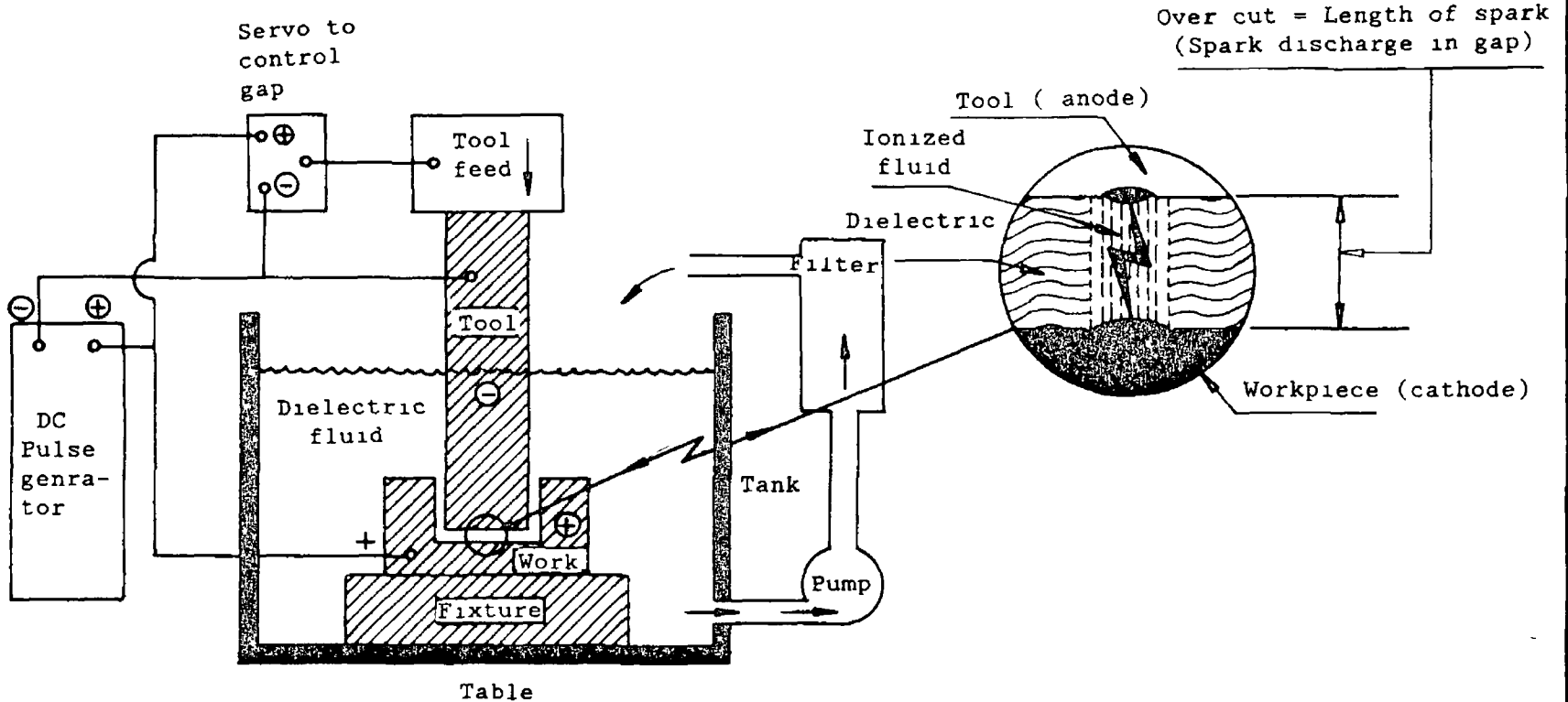
**Figure 18. Shows a schematic diagram of the EDM process
and an over cut**

RESISTANCE (R)

A

DC SUPPLY
Vs

CAPACITOR (C)   Vc

TOOL ELECTRODE (-)

Vb   BREAKING
VOLTAGE IN
GAP

WORKPIECE(+)

B

Vs   SUPPLY VOLTAGE
Vb   GAP BREAKDOWN
          VOLTAGE

CHARGING
VOLTAGE
Vc

TIME, t (micro seconds)

CHARGING   DISCHARGING
TIME   TIME
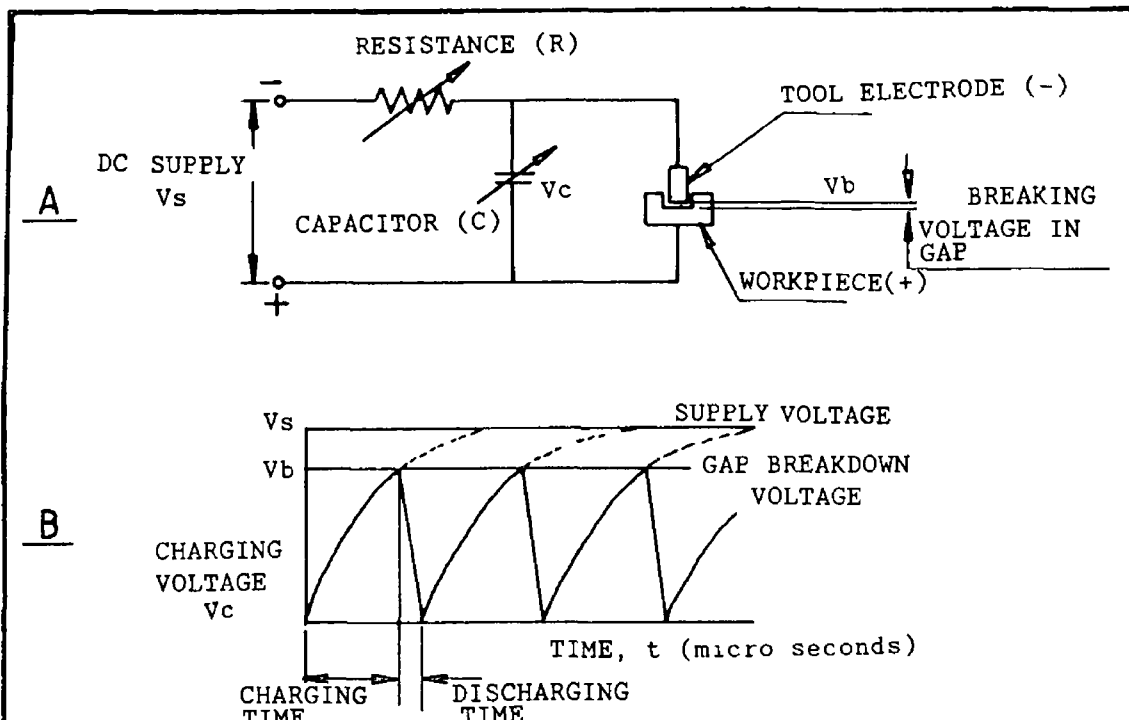
Figure 19. (A) A basic relaxation (RC) circuit
           (B) Relationship between charging
               voltage and time

DC
SOURCE

IMPEDANCE

TIME BASE
FOR 'OFF' TIME

TIME BASE
FOR 'ON' TIME

DETECTOR
UNIT
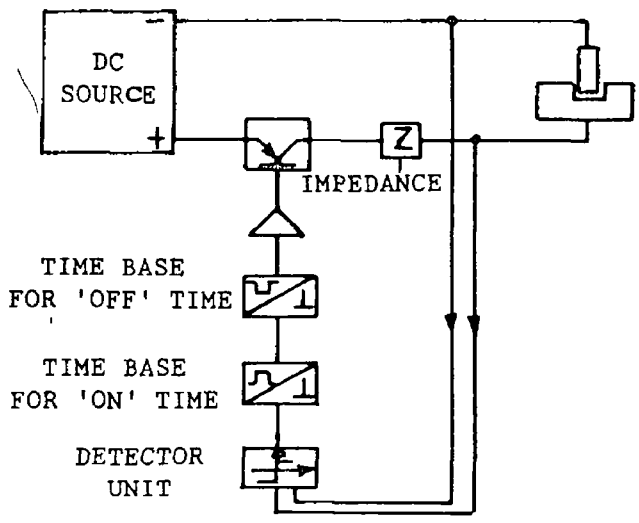
Figure 20 . Shows the principle of the isopulse generator

DISCHAGRE
'ON' TIME   RECOVERY
DELAY D   'OFF' TIME

V

t (Micro seconds)
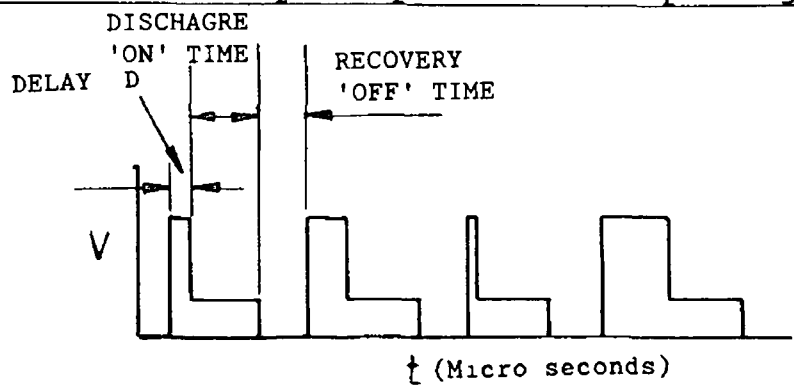
Figure 21. Discharge characteristics of the isopulse
           generator circuit
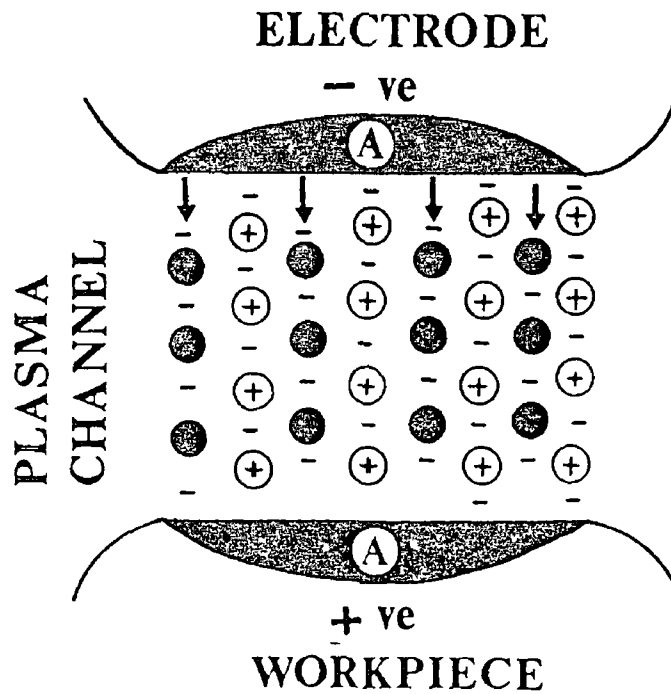
Figure 22. Shows arcing process during EDM

TOP VIEW

WORK

SPARK
GAP

WIRE

SLOT

WIRE
Diam

MOVING
WIRE
ELECTRODE

COPPER
OR TUNGSTEN WIRE

PROGRAMMED
OR NC
WORKPIECE MOTION

SPARK GAP

WORKPIECE

NOZZLES FOR
DIELECTRIC
(DEIONIZED
WATER)
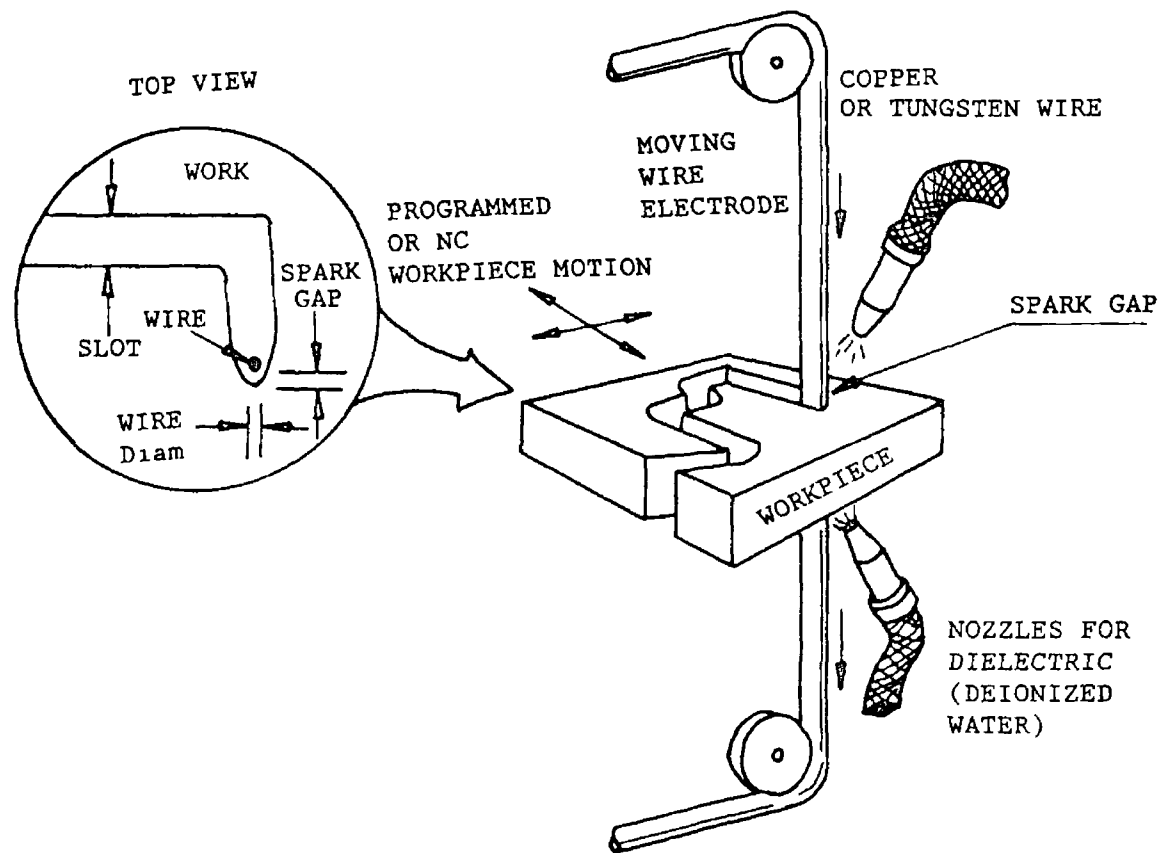
Figure 23. A schematic diagram of Electro-Discharge Machining
(EDM) using the moving wire electrode.

CHAPTER TWO

DESIGN, MATERIAL, EQUIPMENT SELECTION AND FABRICATION
OF THE MANIPULATOR

2.1. INTRODUCTION

This chapter concerns with design, equipment and fabrication of the precision robotic manipulator. The criteria of the design is that, the manipulator should be facilitated, so that, it would generate 2-D / 3-D external / internal complex shapes having more angular cutting facility than currently achievable using commercial WEDM machines.

The commercially available CNC-WEDM machines could provide ±30° taper cut at 12 mm thick workpiece and the tapered cutting facility reduces by increasing the workpiece thickness. This purpose built robotic precision manipulator being studied here can provide upto ±70° and ±65° around X and Y-axes respectively, if the cutting wire is at the centre of the workpiece (maximum 50 mm thick). These tapered cutting facilities reduces according to equations (i), (ii) and (iii) as described in the later sections.

The idea of designing such a manipulator is based on the non-traditional machining processes in which the

mechanical forces are relatively negligable, e.g., EDM, ECM, and LBM processes. For using this manipulator, to generate 3-D complex shapes on present WEDM machines, it should have a least four axes for manipulating the workpiece. **Figure 24** shows a plan view of the robotic precision manipulator which represents four degrees of freedom. This simplicity of design has two main advantages. Firstly, it becomes less costly, easily portable and independent of the machine itself. Secondly, controlling four axes is much easier than larger number of axes to control, since, there is already a large number of variables in WEDM process to be controlled and monitored. A micro computer based software can be used to control the robotic manipulator. **Plate 1** shows a photograph of the manipulator and the wire cutting unit This precision robotic hand can be used for manufacturing extrusion dies, press tools, carbide samples and gears etc.

The step by step design procedure for the manipulator is outlined below.

2.2. MANIPULATOR STRUCTURE AND ASSEMBLY

The manipulator is a purpose built robotic end effector, having four degrees of freedom, two of them are for linear motions along X and Y-axes, and two for rotary motion around X-axis (pitch) and around Y-axis (roll). **Plate 2** shows a photograph of a full general layout of the

equipment which have been used in this research work. Total weight of the manipulator is approximately 55 kilograms. The material used for manufacturing the main parts of the manipulator is aluminium alloy (BS HE30 TF), which has tensile strength of 280 MN/m², steel shafts used are of $\phi 30$ mm, $\phi 20$ mm, and $\phi 16$ mm, having hardness of 60 HRC.

For simulating WEDM process, if the wire is kept at the centre of the workpiece, then maximum pitch and roll angles acheived will be ±70° and ±65° respectively. By referring to **figure 25** this angular facility of pitch and roll reduces as the workpiece travels along Y and X-axes linearly according to the following expression.

$$\pm \text{Pitch (alpha)} = 90 - [\ \tan^{-1}\{\ 17.5/(60-D_y)\ \}\ ] \underline{\qquad} \textbf{(i)}$$

Where D_y = Distance to be travelled from centre of the workpiece (zero) along Y-axis in CW or CCW (± ve) directions (maximum 60 mm)

$$\pm \text{Roll (beta)} = 90 - [\ \tan^{-1}\{\ 17.5/(50-D_x)\ \}\ ] \underline{\qquad} \textbf{(ii)}$$

Where D_x = Distance to be travelled from centre of the workpiece (zero) along X-axis in CW or CCW (± ve) directions (maximum 50 mm).

Figure 26 shows a diagramatic representation of the manipulator. The full assembly drawing of the manipulator and wire cutting unit **(WCU)** is shown in **figure 27 (DRG. NO. 01)**.

TABLE 1

The following tree have been followed for the robotic manipulator and the wire cutting unit (WCU) drawings from full assembly drawing (DRG. NO 01) to each individual drawing part.

```
┌─────────────────────────────────────────────────────┐
│              Figure 27 - Drawing No. 01               │
│  (The Robotic Manipulator and the Wire Cutting Unit)  │
└─────────────────────────────────────────────────────┘
```

Figure 28 DRG. No. 01A (WCU)	Figure 31 DRG. No. 01B (MUA$_r$ X-axis)	Figure 36 DRG. No. 01C (MUA & around Y-axis)	Figure 43 DRG. No. 01D (The Base & MUA X-axis)

Fig. No.	DRG. No.	Fig. No.	DRG. No.	Fig. No.	DRG. No.	Fig. No.	DRG. No.
29	01A01	32	01B01	37	01C01	44	01D01
29	01A02	32	01B02	38	01C02	45	01D02
29	01A03	32	01B03	39	01C03	46	01D03
29	01A04	33	01B04	39	01C04	45	01D04
29	01A05	33	01B05	40	01C05	47	01D05
30	01A06	34	01B06	41	01C06	47	01D06
30	01A07	34	01B07	41	01C07	48	01D07
30	01A08	35	01B08	42	01C08	48	01D08
30	01A09	34	01B09	42	01C09	49	01D10
30	01A10	35	01B10	42	01C10	49	01D11
30	01A11	34	01B11	41	01C11	45	01D12
30	01A12	33	01B12	41	01C12	44	01D13
		35	01B13	37	01C13	49	01D14
		33	01B14	37	01C14		
		33	01B15				
		33	01B16				
		35	01B17				
		32	01B18				
		33	01B19				
		32	01B20				

MUA=Manipulation Unit Along-MUA$_r$=Manipulation Unit Around

The full assembly drawing is sub-divided in to four main parts known as; (1) The Wire Cutting Unit. (2) The manipulation unit around X-axis. (3) The manipulation unit along and around Y-axis. (4) The base and manipulation unit along X-axis.

Figure 27a shows the external dimensions of the manipulator and the **WCU**, and their main functional parts. **Table 1** shows the tree diagram of the drawings from full assembly to each individual part of the working drawing of the manipulator. All of these drawings listed in table 1 are in reduced scale. The full scale drawings are given at the end of the volume two. Each of these four main parts are described below.

2.3. THE WIRE CUTIING UNIT

This sub-assembly drawing of the Wire Cutting Unit is shown in **figure 28**. **Figure 28a** shows its main working parts and external dimensions. Main parts of this unit are fabricated from aluminium alloy. This detachable **WCU** can be manually positioned with respect to the robotic manipulator within it's working area, as required for particular shape to be machined.

The requirements for the **WCU** design are:

(1) It should allow for this simulated **WEDM** process to be

carried out in all linear and rotary axes.

(2) It should rigidly maintain the vertical position of the cutting wire.

(3) It should be manufactured in such a way so that the micro-switch (see figure 30, DRG. NO. 01A12) can be adjusted in a desired position.

The resistance wire used for cutting purpose is bought from Griffin company (Bare constantant wire (Eureka), ECW-280-270M), has the composition of 55% copper, 44% nickel and 1% manganese alloy of $\phi 0.23$ mm. It has the temperature coefficient of resistance $22 \times 10^{-6}/°C$, and resistance of 12.6 ohms per meter at 20°C.

2.4. MANIPULATION UNIT AROUND X-AXIS

This sub-assembly drawing is shown in figure 31. Figure 31a shows it's main working parts and dimensions. This unit consists of mainly two 'C' frames; the inner 'C' frame and the outer 'C' frame.

The inner 'C' frame is contructed of mainly three basic parts (figure 32, DRG. No. 01B01, 01B02 and 01B03). The workpiece size of 120 mm X 120 mm upto 80 mm thick can be housed for machining on this inner 'C' frame. The part No. 01B02 is made up of aluminium alloy, which gives rigidity to this inner 'C' frame and is balanced by two other steel parts (figure 33, DRG. Nos. 01B04 &

01B05). These balancing calculations can be seen in Appendix **A8**. This inner 'C' frame is directly driven by an AC servo-motor (KS-210) in conjuction with a gearbox (Harmonic Drive HDGH 14 - see **figure 27a**) having a gear ratio of 100:1 The choise of the brushless AC servo-motor was studied to be more suitable for the controlling this robotic manipulator, since it can be programed for different resolution, provides brushless resolver feedback to the servomotor KS-drive for enhanced accuracy, produces more torque ratios and is specially designed for this interfacing system.

This gear box is housed on a gear box adaptor **(figure 33, DRG. No. 01B12)**, which is fixed on a right arm of the outer 'C' frame **(figure 34, DRG. No. 01B09)**. The motor torque requirement calculations for this motor are given in Appendix **A3**.

The outer 'C' frame is made up of five basic main parts, the right arm, the left arm, the support beam, the motor balancing part and the gear box balancing part **(figure 34, DRG. Nos. 01B09, 01B11 - figure 35, DRG. Nos. 01B10, 01B17, and figure 33, DRG. No. 01B16)**. The drawing part Nos. 01B11, 01B16 and 01B17 are made up of mild steel, which maintain the balance for a motor, a gear box, a gear box adaptor, right arm of outer 'C' frame and it's supporting bars which are made up of aluminium alloy. This balancing calculations are shown in Appendix **A9**.

The right arm of outer 'C' frame is connected to the main beam **(figure 35, DRG. No. 01B10)** by two M8x1.5 Hexagon Socket Head Cap **(HSHC)** screws. The main beam calculations can be seen in Appendix **A10**. The left arm of this frame and motor balancing bar are connected to the main beam by three M8x1.5 **HSHC** screws. These **HSHC** screw calculations are given in Appendix **A11**. This main support beam is then connected to the main body of the manipulator by a steel shaft of ϕ30 mm. Both of these 'C' frames are assembled together by means of two ϕ10 mm shafts **(figure 32, DRG. No. 01B18 and figure 33, DRG. No. 01B19)**. One of the shaft **(01B19)** is rigidly coupled with gear box (Harmonic Drive HDGH 14) shaft. This gearbox has a maximum backlash of 3 minutes. There is a double sealed deep grove ball bearing (FAG No. 6000 2RSR) having internal diamater of 10 mm housed in the right arm of outer 'C' frame, through which a driven shaft passes and goes into the part **(figure 32, DRG. No. 01B20)** of inner 'C' frame. The other shaft of ϕ10 mm, which connects the other sides of the frames, is engaged with two other deep grove ball bearings housed in the outer and the inner 'C' frames in opposite directions.

Any of the linear or rotary motion, or combination of any of these motions results in movement of the inner 'C' frame of the manipulator, on which the workpiece is housed. The workpiece of dimensions of 120 mm x 120 mm of different thicknesses (Z-co-ordinate) can be housed and machined on the manipulator. The angular machining

facility of pitch (alpha) upto 50 mm thickness of the workpiece can be achieved according to equation (i). This rotary motion of the pitch in CW (-ve) direction reduces from -70° to -30°, if the workpiece thickness is more than 72 mm. Angular manipulation more than -32° at 72 mm workpiece thickness will cause the top edge of the workpiece in touch with the support bar of the main beam (DRG. 01B14). The pitch motion in CW (-ve) direction changes fom 70°, if the workpiece thickness is more than 50 mm according to the following equation (iii) Otherwise, the workpiece top edge will be in touch with M10 Hex cap screw (see figure 31a No. 6).

$$-\text{Pitch} = [\ 6° + \tan^{-1}(60\ /\ \text{ZT})\ ]\ -\ 90° \underline{\hspace{1cm}}(iii)$$

where ZT = workpiece thickness in mm.

The motor for this alpha manipulation can travel an angular distance of 7.2×10^{-4} degrees per full motor step By referring to topic **3.13. Brushless Servomotors,** at ouput nominal and peak motor torque values of 0.1143 Nm and 0 2853 Nm, the torque generated by the gear box (HDGH 14) having an efficiency of 70%, will be

$$T_{(gear\ box)} = T_{(motor)} \text{ X ratio X } \eta$$

Nominal torque generated T_{gb} = 0.1143 X 100 X 0.7

$$\approx 8\ \textbf{Nm}$$

Peak torque generated T_{gb} = 0.2853 X 100 X 0.7

$$= 19.97 \approx 20\ \textbf{Nm}$$

2.5. THE MANIPULATION UNIT ALONG AND AROUND Y-AXIS

The sub-assembly drawing of this central part of the manipulator is shown in **figure 36. Figure 36a** shows it's main working parts and dimensions.

The manoeuvering part along Y-axis **(figure 40, DRG. No. 01C05)**, which hosts two linear compact ball bushings (STAR No. 0658-116-40 x2), and a nut **(figure 41, DRG. 01C12)** is supported by two steel shafts of $\phi16$ mm each **(figure 37, DRG. NO. 01C13)** as shown in figure 36 / 36a. These calculations of the shaft $\phi16$ mm are given in Appendix **A5**. This part is controlled by an AC servo-motor KS-220 (see figure 36). The motor is fixed on motor 'support number 2' **(figure 42, DRG. No. 01C08)**. The lead screw **(figure 37, DRG. NO. 01C14)** is connected to the motor shaft by means of a flexible coupling (Compumotor No. CPG. 2-6) and is supported by two double sealed deep groove ball bearings (FAG No. 6000-2RSR) housed in a 'motor support unit 2' and in a 'main shaft housing unit' **(figure 38, DRG. No. 01C02)**. This motor can travel a linear distance of 3.0 x 10^{-4} mm per full motor step. Total linear distance of 130 mm can be travelled by this motor. The maximum beta motion in CW (-ve) direction can be acheived up to -50°. If this motion is more than -50° then the motor number four (for alpha motion) will be in touch with the base table. The torque calculations for this motor can be seen in Appendix **A2**.

The axial force generated by this motor after accounting for the friction between the lead screw and the nut will be

$$T = F \times r \frac{(\tan\alpha + \mu)}{1 - \mu\tan\alpha} \qquad \text{(iv)}$$

By simplifying (iv) we get

$$F = T \left[(1 - \mu \tan\alpha) / \{ r(\tan\alpha + \mu) \} \right] \underline{\qquad} \text{(v)}$$

Where the nominal output torque of the motor T_n =0.43 N

Peak output torque of the motor T_p =1.29 N

Co-efficient of friction (μ) between the lead screw (carbon steel) and a nut (bronze) for lubricated surfaces taken from machinary hand book (22nd edition) μ =0.16

Effective diameter of the lead screw (M10X1.5)

$$d = 9.026 \times 10^{-3} \text{ m}$$

Radius of the lead screw $r = 4.513 \times 10^{-3}$ m

Therefore $\tan\alpha = \text{Pitch} / (\pi \times d)$

$$= 1.5 \times 10^{-3} / (\pi \times 9.026 \times 10^{-3})$$

$$\tan\alpha = 5.289883 \times 10^{-2}$$

By putting these values in (v) the continuous axial force (F_{ca}) generated by the motor at a nominal torque of T_n = 0.43 Nm will be

$$F_{ca} = 0.43 \frac{[1 - (0.16 \times 5.289883 \times 10^{-2})]}{0.004513 \ (0.052899 \times 0.16)}$$

$$= 0.43 \frac{(9.9153619 \times 10^{-1})}{0.00096081}$$

$$= 0.43 \ (1031.977)$$

$$F_{ca} = 443.7 \approx 443 \text{ N}$$

Therefore maximum axial force (F_{ma}) generated by the motor at peak torque of T_p = 1.29 Nm will be

$$F_{ma} = 1.29 \ (1031.977) \approx 1331 \text{ N}$$

At the central top part of the sliding piece (main motor support unit) along Y-axis (figure 36, part No. 8), there is an AC servomotor (KS-220) in conjunction with a gear box (Drivematic No. SA1002) having gear ratio of 18:1. This gear box has a nominal backlash of 1°. This motor generates roll motion around Y-axis. The gear box is attached to the shaft of $\phi 30$ mm by a rigid coupling. This shaft of $\phi 30$ mm passes through two ball bushings (for combined linear and rotary motion STAR No. 0667-030-00) and is attached to the 'main beam' of the outer 'C' frame The calculations related to this shaft of $\phi 30$ mm are given in Appendix A7. This shaft travels linearely along Y-axis and rotates around Y-axis as well, if there is a motor shaft rotation in the corresponding motors.

This motor for roll motion can travel an angular distance of 4.0×10^{-3} degrees per full motor step at a maximum torque of 17 Nm. This motor torque calculations are given in Appendix A4. The gear box (Drivematic SA 1002, 18:1) has an efficiency of 75%. The nominal and peak torque values generated by this gear box will be

$$T_{(gear\ box)} = T_{(motor)} \times ratio \times \eta$$

Nominal torque generated T_{gb} = 0.43 X 18 X 0.75

= 5.8 Nm

Peak torque generated T_{gb} = 1.29 X 18 X 0.75

= 17.41 Nm

2.6. THE BASE AND MANIPULATION UNIT ALONG X-AXIS

This sub-assembly drawing is shown in **figure 43**. **Figure 43a** shows it's main working parts and dimensions.

The base **(figure 41, DRG. No. 01C11)** of the Y-axis manipulation unit is attached to the X-axis manoeuvering part **(figure 44, DRG. No. 01D01)** of this unit by four M12 **HSHC** screws. This X-axis manoeuvering part **(DRG. No. 01D01)** is supported by two steel shafts of $\phi20$ mm **(figure 48, DRG. 01D08)** on which it slides by means of four linear compact ball bushings (STAR No. 120-0658-40) has central screw / servomotor (KS-220) arrangement as in Y-axis manoeuvering part. These two steel shafts of $\phi20$ mm and lead screw **(figure 48, DRG. No. 01D07)** are supported by 'X-axis supporting plate' **(figure 47, DRG. No. 01D05)** and 'motor support unit 1' **(figure 49, DRG. No. 01D10)**. The $\phi20$ mm shaft clculations are given in Appendix **A6**.

The maximum distance of 240 mm can be travelled by this manoeuvering part along X-axis This motor can travel a minimum linear distance of $3.0x10^{-4}$ mm per full motor step. This motor torque calculations are given in Appendix **A1**. This motor for X-axis manipulation can generate a continuous axial force of 443 **N** and maximum axial force of 1331 **N** after accounting for the friction between the lead screw and the nut.

The base part (figure 46, DRG. NO. 01D03) has two main functions firstly, it supports the whole manipulator, secondly it permits X-axis motion of the manipulator.
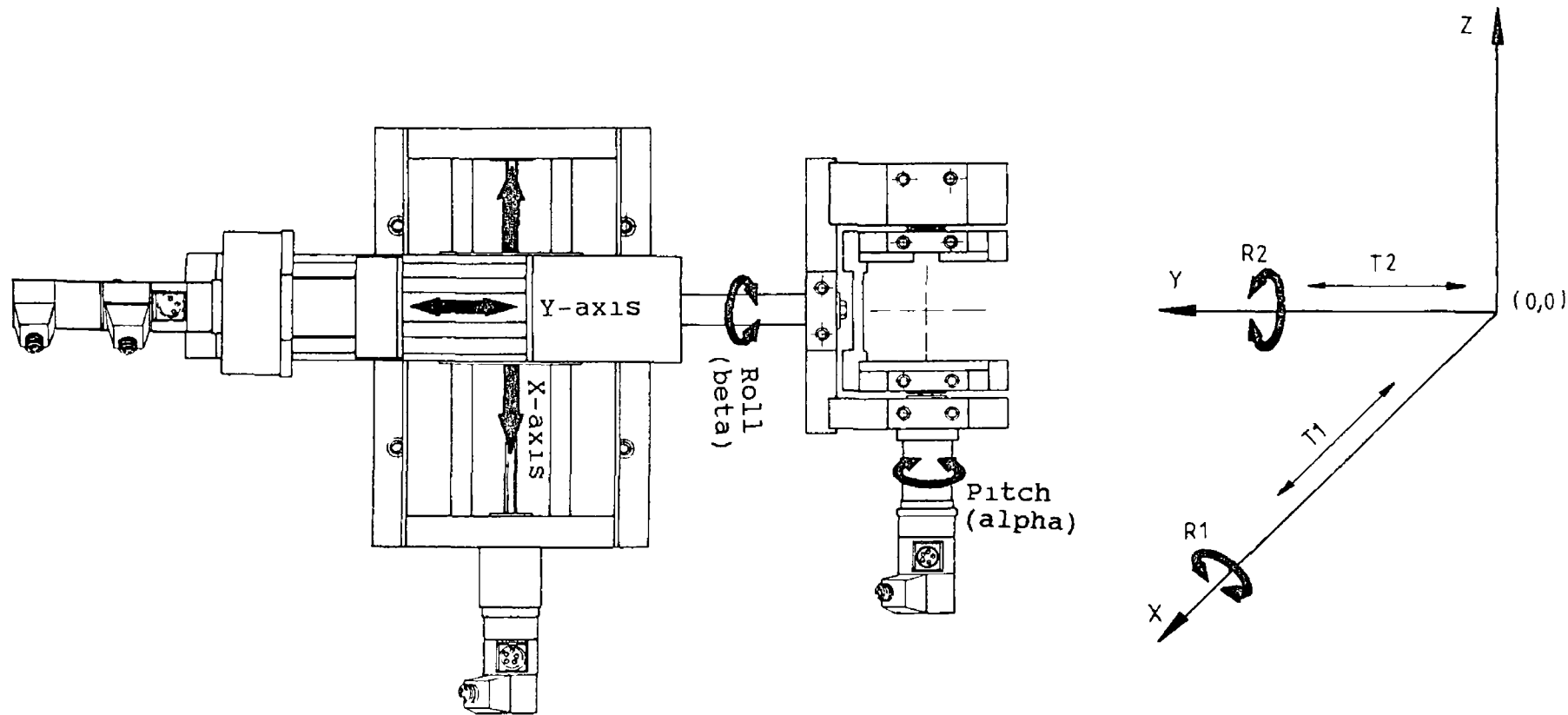
Figure 24. Shows a plan view of the robotic manipulator, which represents four degrees of freedomn, two translation (T1 and T2) and two rotary motions (R1 and R2).
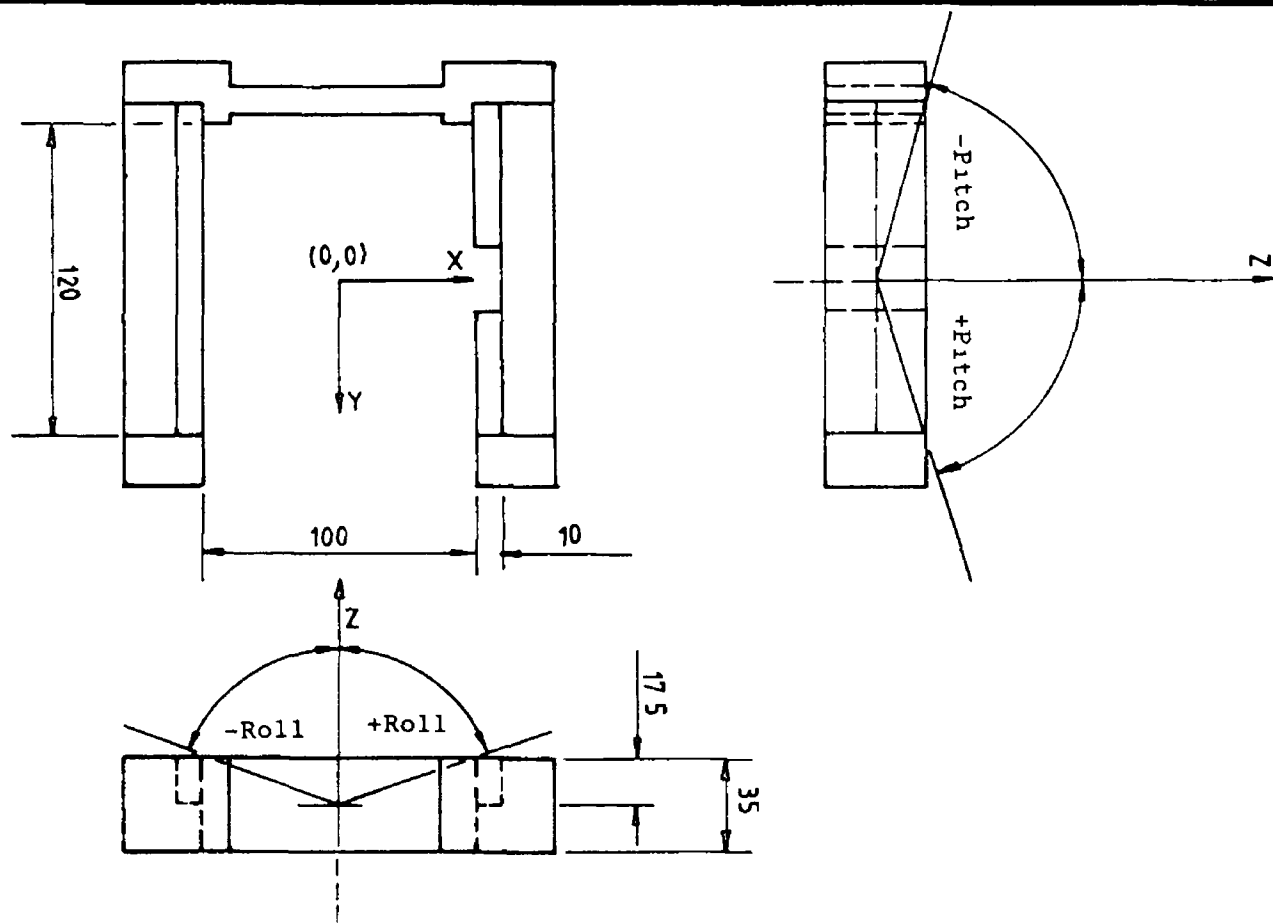
Figure 25. Shows the workpiece gimbaling part of the manipulator, which shows the angular cutting facility around X and Y-axes (Pitch and Roll)

Figure 26. Shows a diagramatic representation of the
manipulator.

FIGURE 27

ORG NO	DESCRIPTION	NO
01A	WIRE CUTTING UNIT	1
01B	MANIPULATION UNIT AROUND X-AXIS	2
01C	MANIPULATION UNIT ALONG AND AROUND Y-AXIS	3
01D	THE BASE AND MANIPULATOR UNIT ALONG Z-AXIS	4

DRG BY M.T BHATTI

SCHOOL OF MECHANICAL AND MANUFACTURING ENG.

DUBLIN CITY UNIVERSITY

TITLE

THE ROBOTIC MANIPULATOR

DATE 5th January 1998

UNIT mm   SCALE 1:1

DRAWING NO   0.1

END VIEW

ELEVATION

130

1270

PLAN

END VIEW

440

616

NO	DESCRIPTION
1	ROTATING MOTION AROUND X-AXIX
2	ROTATING MOTION AROUND Y-AXIX
3	Y-AXIX MANOEUVRING MOTION
4	X-AXIX MANOEUVRING MOTION
5	DRIVEMATIC GEARBOX NO SA 1002 (18 1)
6	COMPUMOTOR COUPLING NO CPG 2-6
7	MS TYPE MOTOR CONNECTOR
8	MS TYPE RESOLVER FEEDBACK CONNECTOR
9	HARMONIC DRIVE GEARBOX NO HDGH14 (100 1)
10	TENSION SPRING
11	CUTTING WIRE

ALL DIMENSIONS ARE IN MILIMETERS **FIGURE 27a**

ELEVATION

PLAN

END VIEW
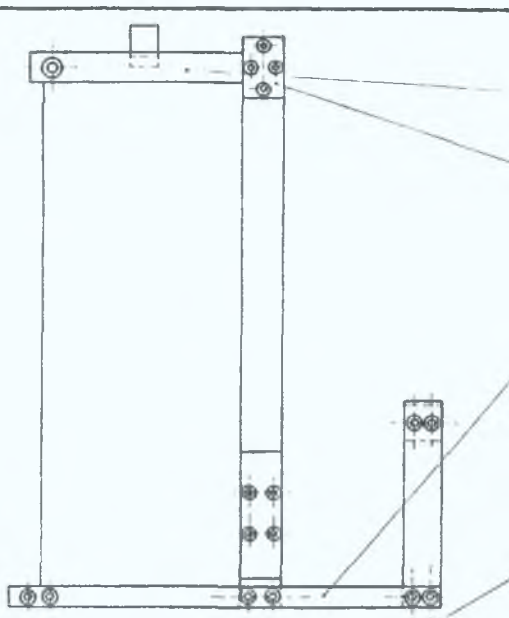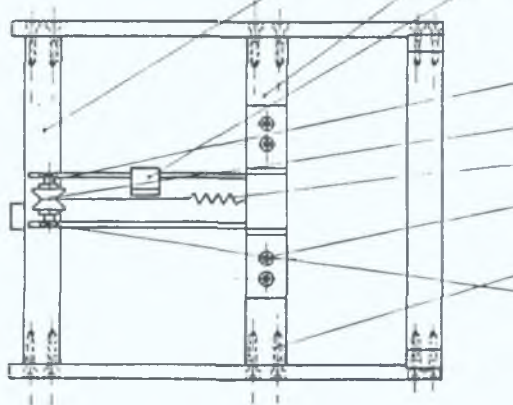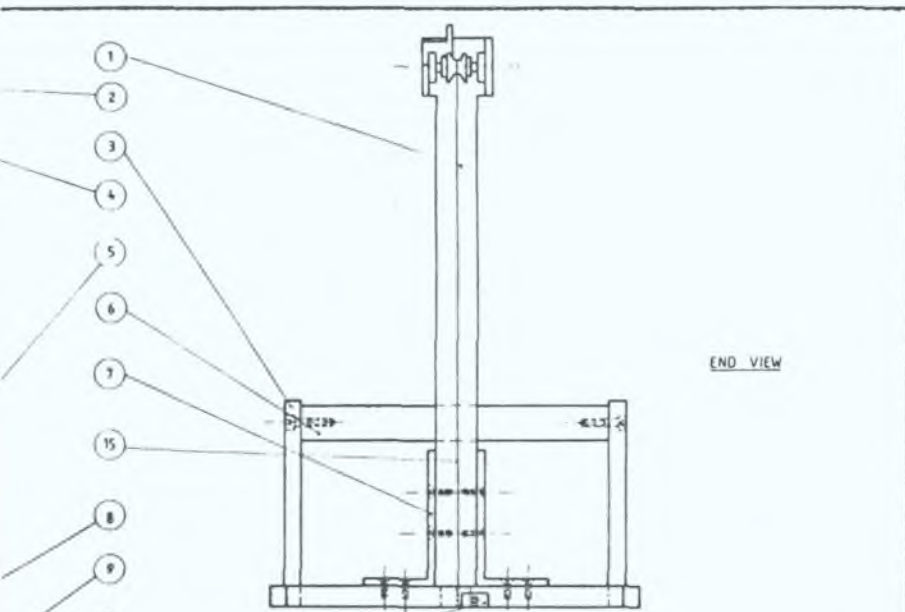
No	Quantity	DESCRIPTION	Material	Draw
18	1	MICRO SWITCH ADJUSTER	ALUMINIUM ALLOY	01A12
17	1	Electrical-Connector		
16	2	Bearings (fag no. 608 2RSR)		
15	1	Cutting wire		
14	1	Spring (tension)		
13	16	Screw M6×20		
12	20	Screw M6×10		
11	1	Pulley	ALUMINIUM ALLOY	01A11
10	1	Pulley Shaft	Steel	01A10
9	1	Column base support	Steel	01A09
8	1	Base	Steel	01A08
7	2	Column support	Aluminium	01A07
6	1	Handy bar	Steel	01A06
5	2	Base-arm	Steel	01A05
4	2	Column arm retainer	Aluminium	01A04
3	2	Base-hand	Steel	01A03
2	2	Column arm	Aluminium	01A02
1	1	Column	Aluminium ALLOY	01A01

DRG. BY M T BHATTI

DATE 1-2-1990

UNIT m.m. SCALE 1:2

SCHOOL OF MECHANICAL
AND MANUFACTURING ENGG

DUBLIN CITY UNIVERSITY

TITLE

WIRE CUTTING UNIT

DRG NO SUB-ASBL DRAWING 01A

FIGURE 28

ELEVATION

END VIEW

① ───────────

440

② ③

PLAN

④ ───────

312

- 86 -
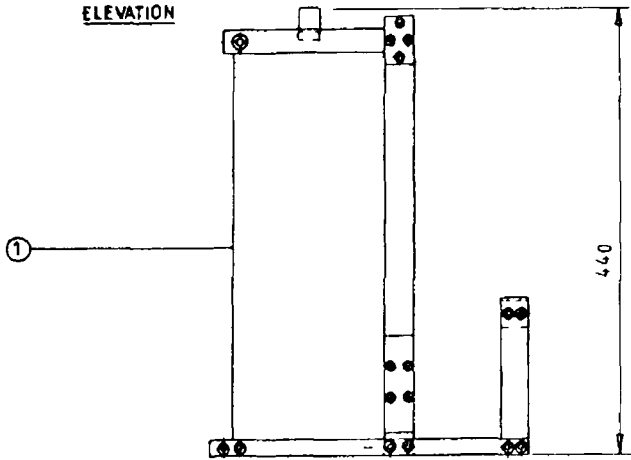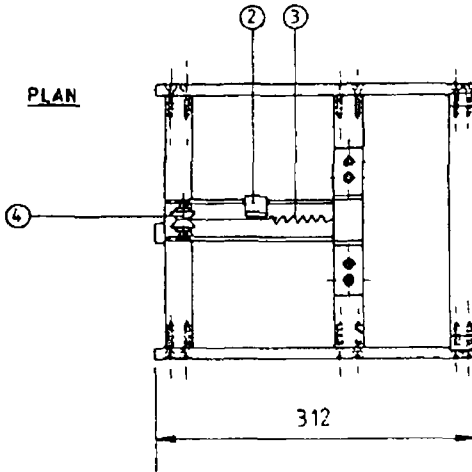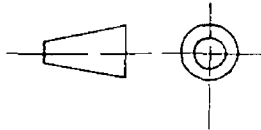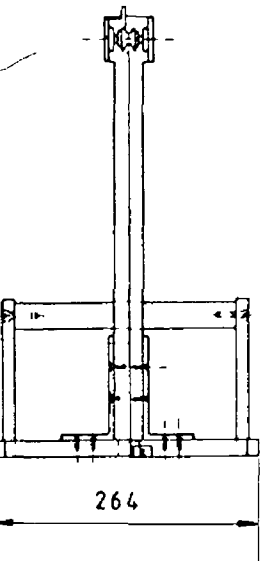
NO	DESCRIPTION
1	CUTTING WIRE
3	TENSION SPRING
2	MICRO SWITCH ADJUSTER
4	PULLEY

264

ALL DIMENSIONS ARE IN MILIMETERS

FIGURE 28a
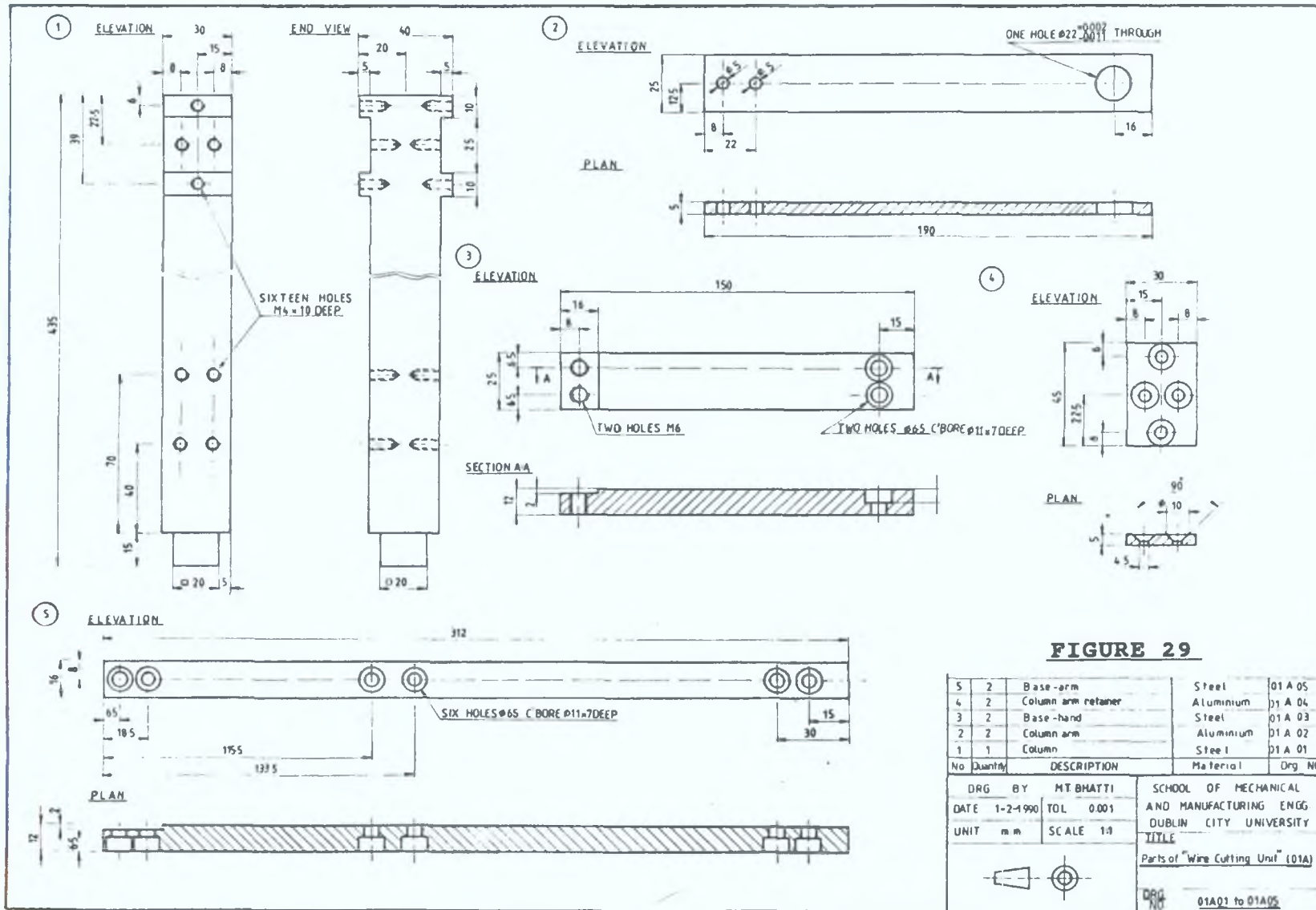
FIGURE 29

No	Quantity	DESCRIPTION	Material	Drg NO
5	2	Base-arm	Steel	01 A 05
4	2	Column arm retainer	Aluminium	01 A 04
3	2	Base-hand	Steel	01 A 03
2	2	Column arm	Aluminium	01 A 02
1	1	Column	Steel	01 A 01

DRG BY M.T. BHATTI	SCHOOL OF MECHANICAL
DATE 1-2-1990 TOL 0.001	AND MANUFACTURING ENGG
UNIT m m SCALE 1:1	DUBLIN CITY UNIVERSITY

TITLE
Parts of "Wire Cutting Unit" (01A)

DRG NO 01A01 to 01A05
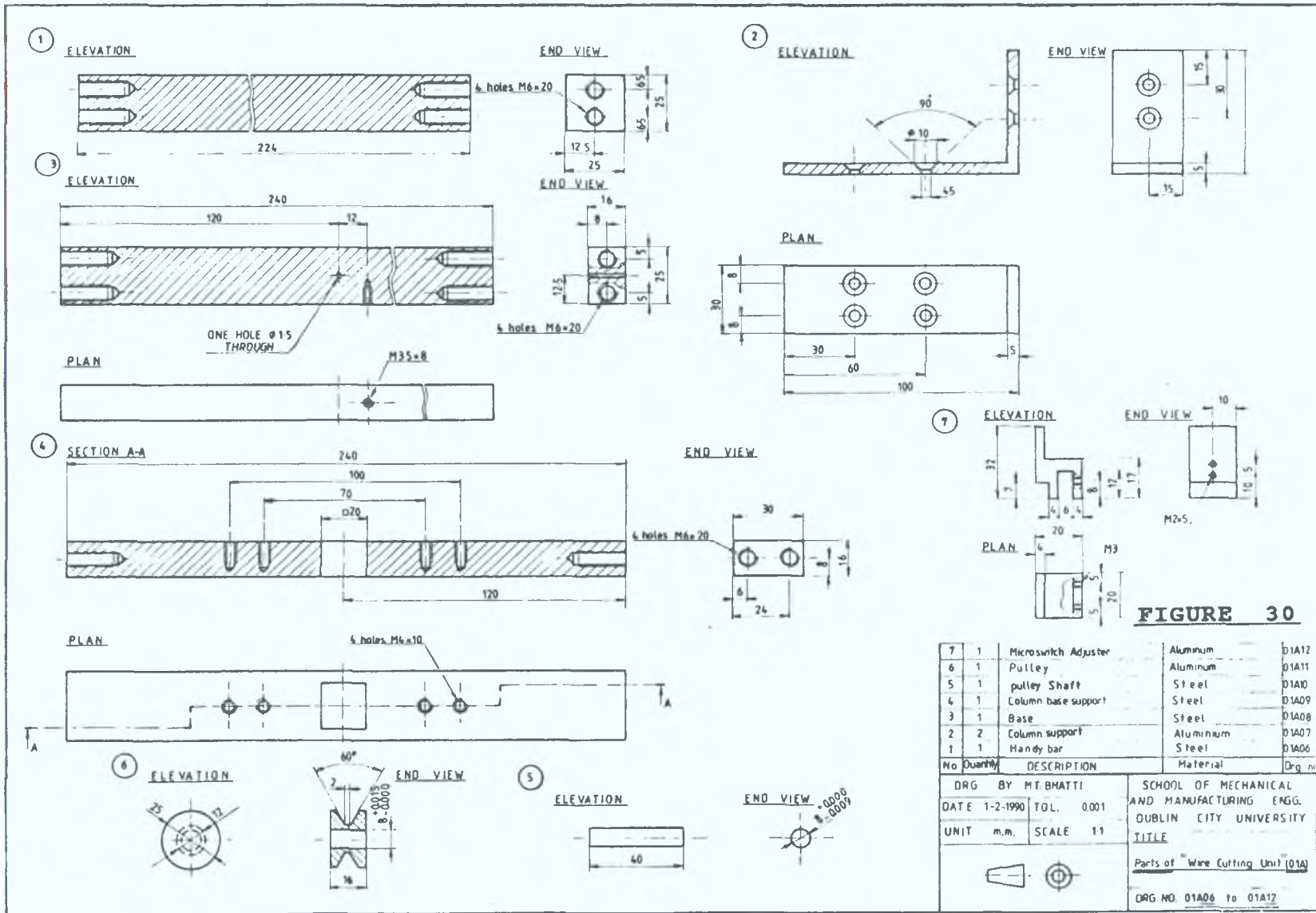
FIGURE 30

No	Quantity	DESCRIPTION	Material	Drg no
7	1	Microswitch Adjuster	Aluminum	01A12
6	1	Pulley	Aluminum	01A11
5	1	pulley Shaft	Steel	01A10
4	1	Column base support	Steel	01A09
3	1	Base	Steel	01A08
2	2	Column support	Aluminum	01A07
1	1	Handy bar	Steel	01A06

DRG BY M.T.BHATTI	SCHOOL OF MECHANICAL AND MANUFACTURING ENGG. DUBLIN CITY UNIVERSITY
DATE 1-2-1990 TOL. 0.001	
UNIT m.m, SCALE 1:1	TITLE
	Parts of Wire Cutting Unit (01A)
	DRG NO. 01A06 to 01A12

- 100 -

ELEVATION

END VIEW

FIGURE 31
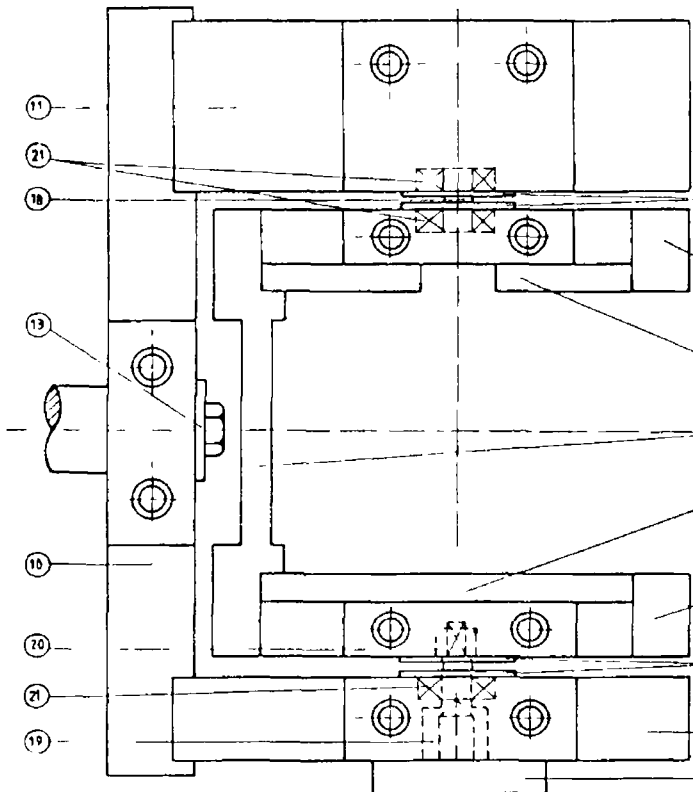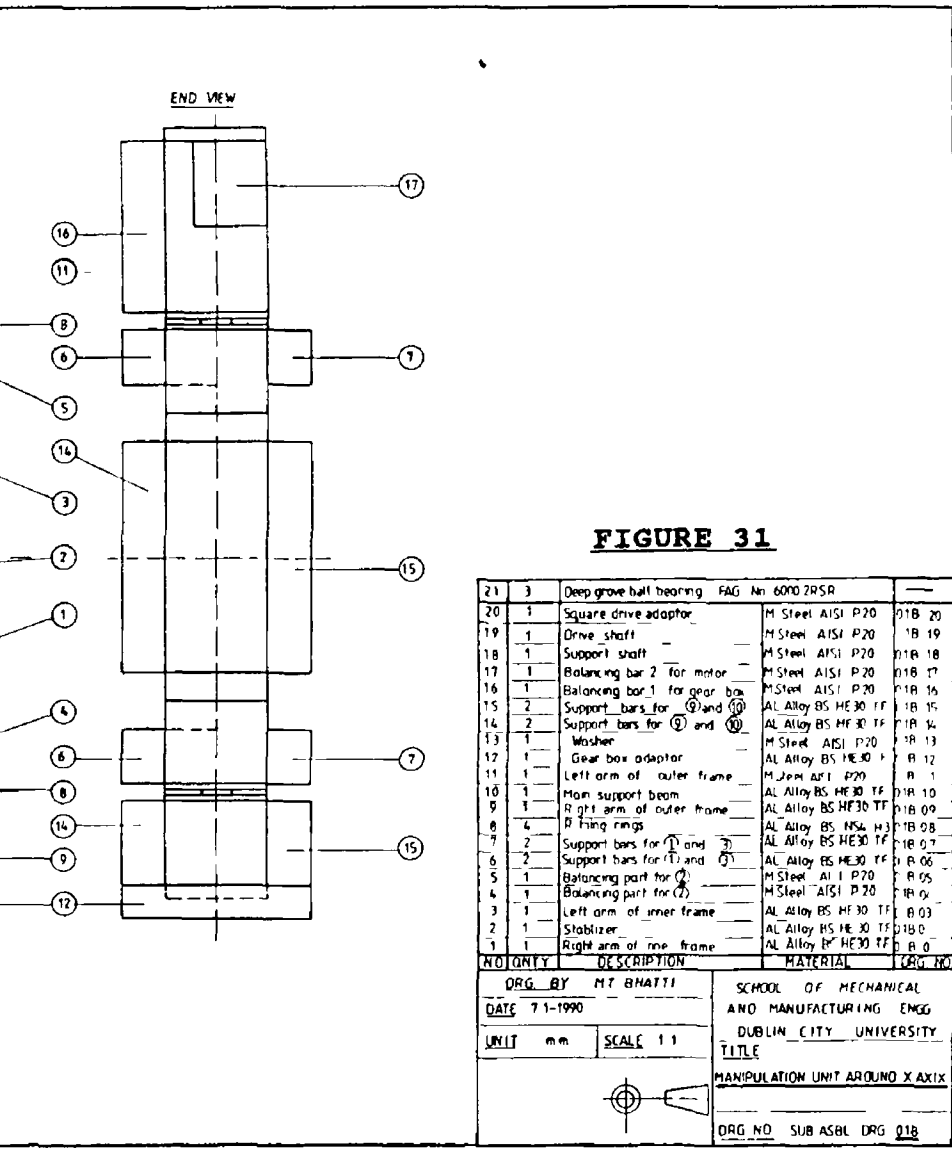
NO	QNTY	DESCRIPTION	MATERIAL	DRG NO
21	3	Deep grove ball bearing FAG No 6000 2RSR	—	—
20	1	Square drive adaptor	M Steel AISI P20	01B 20
19	1	Drive_shaft	M Steel AISI P20	1B 19
18	1	Support shaft	M Steel AISI P20	01B 18
17	1	Balancing bar 2 for motor	M Steel AISI P20	01B 17
16	1	Balancing bar 1 for gear box	M Steel AISI P20	01B 16
15	2	Support_bars for (9) and (10)	AL Alloy BS HE30 TF	1B 15
14	2	Support bars for (9) and (10)	AL Alloy BS HF30 TF	1B 14
13	1	Washer	M Steel AISI P20	1B 13
12	1	Gear box adaptor	AL Alloy BS HE30	B 12
11	1	Left arm of outer frame	M Steel AISI P20	B 1
10	1	Main support beam	AL Alloy BS HE30 TF	01B 10
9	1	Right arm of outer frame	AL Alloy BS HF30 TF	01B 09
8	4	R hing rings	AL Alloy BS NS4 H3	1B 08
7	2	Support bars for (1) and (3)	AL Alloy BS HE30 TF	1B 07
6	2	Support bars for (1) and (3)	AL Alloy BS HE30 TF	B 06
5	1	Balancing part for (2)	M Steel AII P20	B 05
4	1	Balancing part for (2)	M Steel AISI P20	1B 04
3	1	Left arm of inner frame	AL Alloy BS HF30 TF	B 03
2	1	Stablizer	AL Alloy BS HE30 TF	01B 02
1	1	Right arm of inne frame	AL Alloy BS HE30 TF	B 0

ORG. BY MT BHATTI		SCHOOL OF MECHANICAL
DATE 7 1-1990		AND MANUFACTURING ENGG
UNIT mm	SCALE 1 1	DUBLIN CITY UNIVERSITY
		TITLE
		MANIPULATION UNIT AROUND X AXIX
		DRG NO SUB ASBL DRG 01B

PLAN

201

120

II
(−,+)

III
(−,−)

(0,0)

I
(+,+)

IV
(+,−)

10

100

262

⑥ ③

⑦

②

③

⑧

①

r

END VIEW

④ ────── ⑤

NO	DESCRIPTION
1	ROTARY MOTION AROUND X AXIX
2	STAR STEEL SHAFT ϕ30mm
3	TWO SHAFTS ϕ10mm
4	STEEL BALANCING BAR FOR GEAR BOX
5	STEEL BALANCING BAR FOR MOTOR
6	ONE HEX CAP SCREW M10
7	ONE WASHER 3mm THICK
8	THREE DEEP GROVE BALL BEARINGS FAG NO 6000 2RSR

ALL DIMENSIONS ARE IN MILIMETERS

35

65

FIGURE 31a

ELEVATION

92
44
32
15
+00152
+00000
68.0012
-0012
R5
R5
128
35

FOUR HOLES M 8
END VIEW
20
175
26
35
9
TWO HOLES M 6
85
23
30

FOUR HOLES M3 5 45 DEEP
TAPPING DRILL Ø25 6 DEEP

PLAN
35
A
005 A
6
10
16
0182
0182
30
TWO HOLES Ø83 THROUGH

ELEVATION
160
35
26
9
85
23
TWO HOLES Ø615 CBORE Ø105x61 DEEP
FOUR HOLES Ø83C
BORE Ø85 85 DEEP

PLAN
B
005 B
005 A
A
25
17
2
10
40
120
130
160

ELEVATION
128
104
32
22
875
12
68.0012
+0012
32
15

ONE HOLE Ø26
0.008
0.005
8 DEEP
FOUR HOLES M3 945 DEEP
TAPPING DRILL Ø25 6 DEEP
20
FOUR HOLES M 8
175
35
26
9
85
23
30

TWO HOLES M 8 THROUGH
ONE HOLE Ø24 10 DEEP
ONE HOLE Ø11 12 DEEP
TWO HOLES M 6

PLAN
92
44
22
005 B
30
10
12
B
35
555
805
15

SCALE 3 1
ELEVATION
Ø10 h6
16
10
10
Ø13
Ø10 h6 10
END VIEW

DRG NO
SCALE 2 1
□16
+00182
-00182
□7
+00152
00000
R15
R15
ELEVATION

10
END VIEW

FIGURE 32

5	1	Square drive adaptor	M Steel AISI P20	01B20
4	1	Support shaft	M Steel AISI P20	01B18
3	1	Left arm of inner frame	AL Alloy BS HE30 TF	01B03
2	1	Stabicer	AL Alloy BS HE30 TF	01B02
1	1	Right arm inner frame	AL Alloy BS HE30 TF	01B01
NO	QNTY	DESCRIPTION	MATERIAL	DRG NO

DRG BY MT BHATTI	SCHOOL OF MECHANICAL
DATE 9-1-1990 TOL 0001	AND MANUFACTURING ENGG
	DUBLIN CITY UNIVERSITY
UNIT mm SCALE 11	TITLE
	Parts of MANIPULATION UNIT
	AROUND X AXIY [01B]
	DRG NOs 01B01 to 01B03 01x18 and 01B20

FIGURE 33

NO	QNTY	DESCRIPTION	MATERIAL	DRG N°
7	1	Balancing bar 2 for gear box	M Steel AISI P20	01B16
6	1	Gear box adaptor	AL Alloy BS HE 30 TF	01B12
5	1	Drive shaft	M Steel AISI P20	01B19
4	1	Balancing part for ⑦ (ref 01B)	M Steel AISI P20	01B04
3	1	Balancing part for ② (ref 01B)	M Steel AISI P20	01B04
2	2	Support bars for ③④ (ref 01B)	AL Alloy BS HE 30 TF	01B15
1	2	Support bars for ③④ (ref 01B)	AL Alloy BS HE 30 TF	01B14
NO	QNTY	DESCRIPTION	MATERIAL	DRG N°

DRG BY	M T BHATTI		SCHOOL OF MECHANICAL
DATE 8 1 1990	TOL	0001	AND MANUFACTURING ENGG
UNIT m.m	SCALE	1 1	DUBLIN CITY UNIVERSITY

TITLE

Parts of MANIPULATION UNIT AROUND X-AXIX (01B)

DRG N°s 01B14 to 01B16, 01B19 01B12, 01B04 and 01B05

FIGURE 34

ELEVATION

FIVE HOLES ∅83 C BORE ∅135-95 DEEP
ONE HOLE ∅ 30H7-5 DEEP

END VIEW

ELEVATION

5 60 22 36-0.00 +0.016 97 20

35 12.5 20 26 9 0 26 9

20 26 9 30 5

50 127 151 222

R 2

① ② ③ ④

PLAN

⊥ 005 A   ⊥ 005 B

A   B

15

TWO HOLES ∅83 THROUGH

SECTION AA

ELEVATION

∅23 40 5 20 5

17.5 5

A   A

FOUR HOLES ∅32 CSK AT 92 TO ∅61

SECTION AA

ELEVATION

⊥ 005 A

ONE HOLE M8 50 DEEP

END VIEW

25 25
12.5

A

15 30

PLAN

TWO HOLES M8 THROUGH

A

74 122 178 30

⊥ 005 A

FIGURE 35

4	4	Retaining rings	Al Alloy BS NS4 H3	01B06
3	1	Washer	M Steel AISI P20	01B13
2	1	Balancing bar 2 for motor	M Steel AISI P20	01B17
1	1	Main support beam	Al Alloy BS HE 30 TF	01B10
NO	QUNTY	DESCRIPTION	MATERIAL	Dg

DRG BY M T BHATTI	SCHOOL OF MECHANICAL
DATE 12-1 1990	TOL 0001	AND MANUFACTURING ENGG DUBLIN CITY UNIVERSITY
UNIT mm	SCALE 1:1	TITLE

Parts of MANIPULATION UNIT AROUND X-AXIX [01B]

DRG NOs 01B06, 01B10, 01B13, and 01B17

ELEVATION

END VIEW

PLAN

NO	DESCRIPTION	MATL.	QNTY	DRG NO
27	M10 Hexagone socket head cap screws	—	3	—
26	M10 Hexagone socket head cap screws	—	1	01C14
25	Lead screw M10	—		01C13
24	Star steel shaft of ⌀16	Steel	2	01C12
23	Nut	M.Steel	1	
22	Star compact ball bushings for linear motion No. 0658-116-40=2	—	2	
21	The base of Y-axis	Al.Alloy	1	01C11
20	M6 Hexagone socket head cap screws	Al.Alloy	1	01C10
19	Retaining ring	Al.Alloy	1	01C10
18	FAG deep grove ball bearing no 6000-2RSH	—	2	
17	Washers	H.Steel	6	01C09
16	M8 Hexagon socket head screws	—		
15	MOTOR SUPPORT UNIT 2	Al.Alloy	1	01C08
14	COMPUMOTOR Flexible coupling No CPG7-6	—	1	
13	COMPUMOTOR A.C Servomotor No KS-220	—	1	
12	COMPUMOTOR A.C Servomotor NO KS-220	—	1	
11	DRIVEMATIC gear box no SA 100:1 (18:1)	—	1	
10	Adaptor for gear box of ratio 18:1	N.Alloy	1	01C07
9	Coupling	M.Steel	1	01C06
8	Main motor support unit	AL.Alloy	1	01C05
7	FAG Needle roller bearing No RNA 6905A	—	1	
6	Bearing retainer	AL.Alloy	1	01C04
5	M5 Counter sunk screws	—	12	
4	Bearing retainer	N.Alloy	1	01C03
3	Main shaft housing unit	AL.Alloy	1	01C02
2	STAR BALL BUSHINGS FOR COMBINED LINEAR AND ROTARY MOTION NO. 0667-030-00=2	—	2	
1	STEEL SHAFT OF ⌀30 mm	STEEL	1	01C01

DRG. BY M.T. BHATTI

DATE 08-08-89

UNIT mm SCALE 1:2

SCHOOL OF MECHANICAL AND MANUFACTURING ENGG

DUBLIN CITY UNIVERSITY

TITLE MANIPULATION UNIT AROUND AND ALONG Y-AXIS

DRG NO SUB ASSMBLY DRG NO 01C

FIGURE 36

ELEVATION

END VIEW

130

22 5

169 5

241 5

98

56

486

120

PLAN

144

FIGURE 36a

ALL DIMENSIONS ARE IN MILIMETERS

NO	DESCRIPTION
1	LINEAR MOTION ALONG Y-AXIX
2	ROTARY MOTION AROUND Y-AXIX
3	STAR STEEL SHAFT Ø 30 mm
4	STAR BALL BUSHING FOR COMBINED LINEAR AND ROTARY MOTION (TWO) NO 0667-030 00×2
5	FAG NEEDLE ROLLER BEARING ONE NO RNA690SA
6	COUPLING
7	DRIVEMATIC GEAR BOX NO SA1002 (18 1)
8	COMPUMOTOR AC SERVO MOTOR NO KS-220
9	COMPUMOTOR FLEXIBLE COUPLING NO CPG 2-6
10	COMPUMOTOR AC SERVO MOTOR NO KS-220
11	STAR COMPACT BALL BUSHINGS FOR LINEAR MOTION (TWO) NO 0658-116-40×2
12	FAG DEEP GROVE BALL BEARING(TWO) NO 6000-2RSR

1

363
343
313
10

⌀6.35   ⌀8h6   OUTER THREAD M10×1.5   ⌀8h6

ELEVATION   END VIEW

2

466
4
40

⌀10h6   ⌀10h6
35   ⌀16   50

ELEVATION   TWO HOLES M8 1.5   END VIEW

3

488
34
19
25
A
A
⌀30
⌀24
⌀14k6

ONE HOLE M10 70 DEEP   ELEVATION

FIGURE 37   END VIEW

⌀10k6 ⌀10 $^{0.010}_{0.001}$ ⌀8h6 ⌀8 $^{0.009}_{0.000}$ ⌀14 k6 ⌀14 $^{-0.012}_{0.001}$

R2

SECTION A A
SCALE 2.1

22.36 $^{0.000}_{-0.016}$

20 $^{0.000}_{-0.010}$
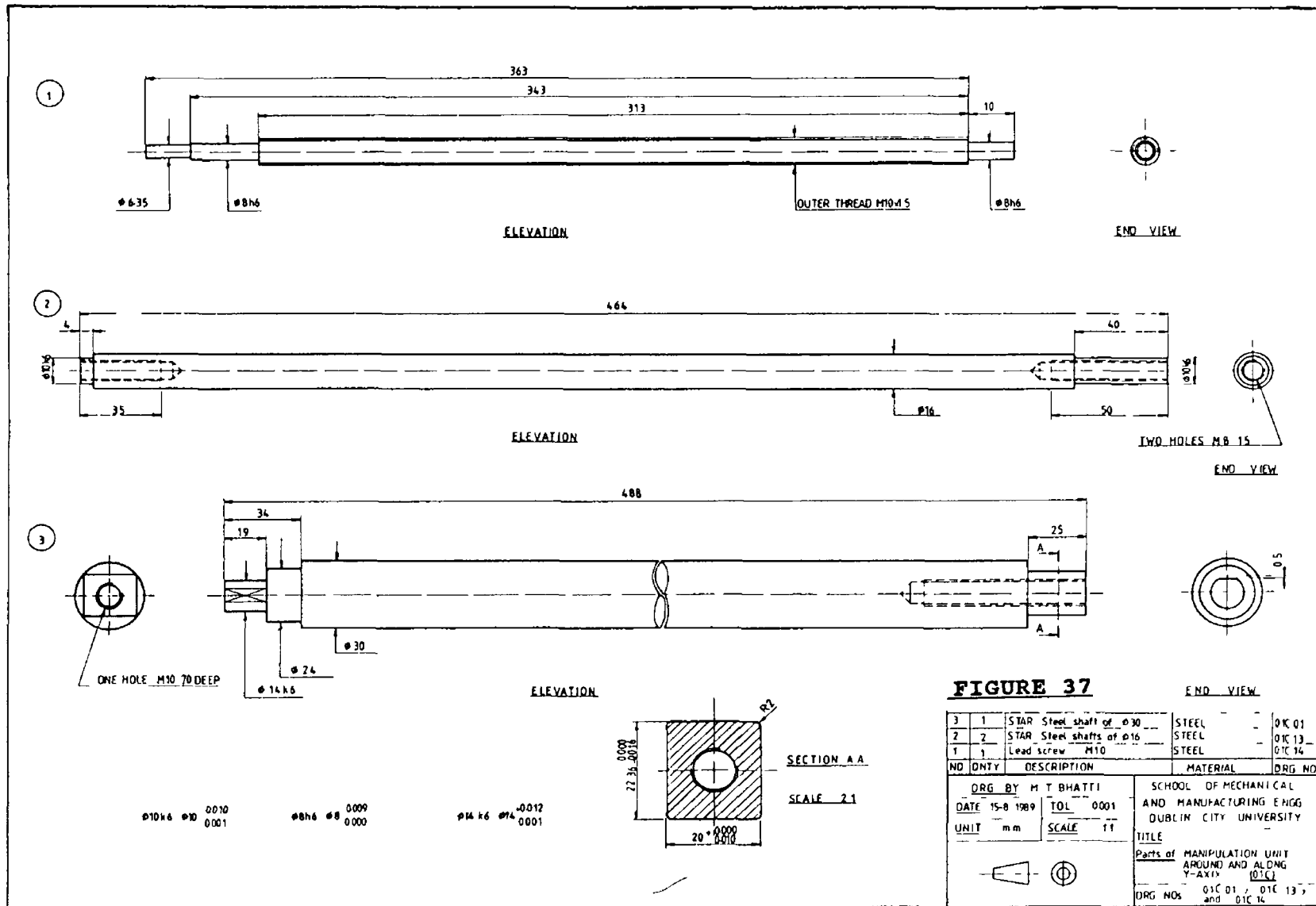
3	1	STAR Steel shaft of ⌀30	STEEL	—	01C 01
2	2	STAR Steel shafts of ⌀16	STEEL	—	01C 13
1	1	Lead screw M10	STEEL	—	01C 14
NO	QNTY	DESCRIPTION	MATERIAL		DRG NO

DRG BY M T BHATTI		SCHOOL OF MECHANICAL
DATE 15-8 1989	TOL 0.001	AND MANUFACTURING ENGG
UNIT mm	SCALE 1:1	DUBLIN CITY UNIVERSITY

TITLE
Parts of MANIPULATION UNIT
AROUND AND ALONG
Y-AXIS (01C)

DRG NOs 01C 01 , 01C 13 ;
and 01C 14
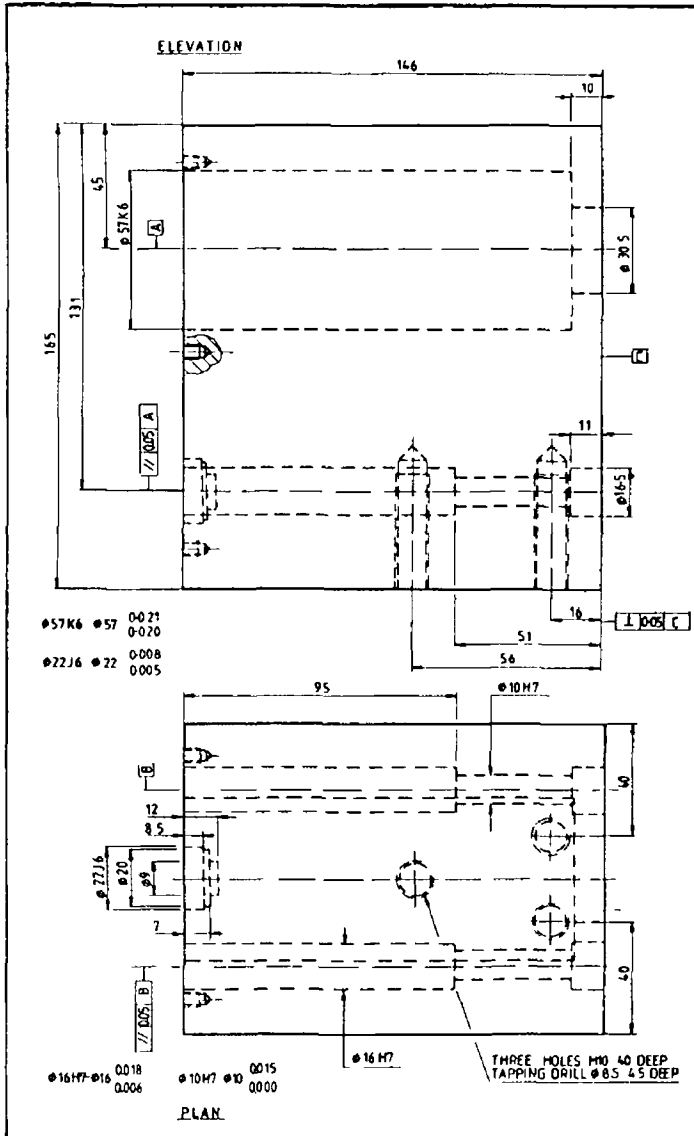
ELEVATION
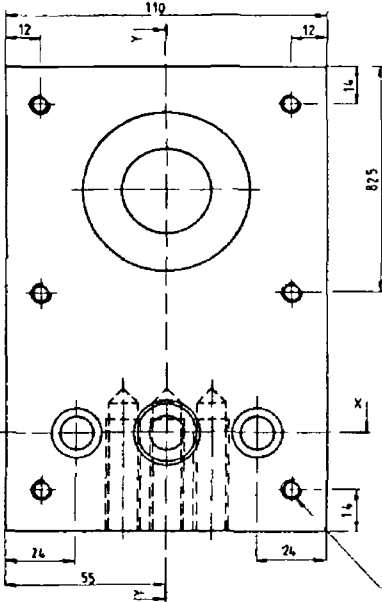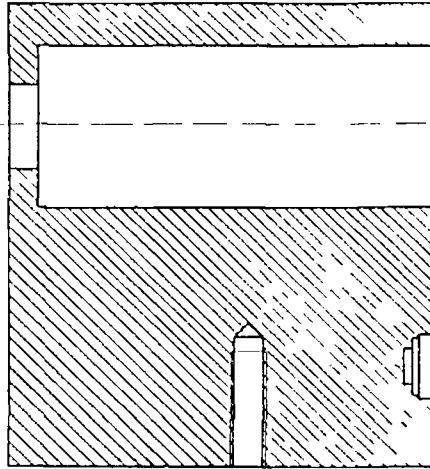
φ57K6 φ57 $^{+0.021}_{-0.020}$

φ22J6 φ22 $^{+0.008}_{-0.005}$

φ16H7=φ16 $^{0.018}_{0.006}$ φ10H7=φ10 $^{0.015}_{0.000}$

THREE HOLES M10 40 DEEP
TAPPING DRILL φ8.5 45 DEEP

PLAN

SECTION Y Y

110

12

Y

12

16

825

16

X

X

24

24

SIX HOLES M-5 8 6 DEEP
TAPPING DRILL Φ4.2 8 DEEP

55

QUANTITY ONE
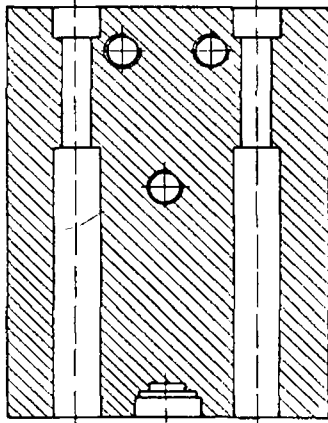
SECTION X X

FIGURE 38

DRG BY M T BHATTI		SCHOOL OF MECHANICAL
DATE 10-8-1989	TOL 0.001	AND MANUFACTURING ENGG
UNIT mm	SCALE 1/1	DUBLIN CITY UNIVERSITY
MATERIAL AL Alloy BS HE30 T F		TITLE
		MAIN SHAFT HOUSING UNIT
		DRG NO 01C02

ONE HOLE φ 40 THROUGH

SIX HOLES φ51 CSK AT 92 φ 10

ELEVATION

TWO HOLES φ20 THROUGH

ONE HOLE φ12 THROUGH

PLAN

106

91

15

15

45

80

167.5

131

160

22

53

84

5

- 111 -

ONE HOLE ⌀ 41 THROUGH

SIX HOLES ⌀51 CSK AT 92 ⌀10

ELEVATION

110
98
12

14
45
82.5
131
151
165

TWO HOLES ⌀17 THROUGH

ONE HOLE ⌀20 THROUGH

24
55
86

5

PLAN
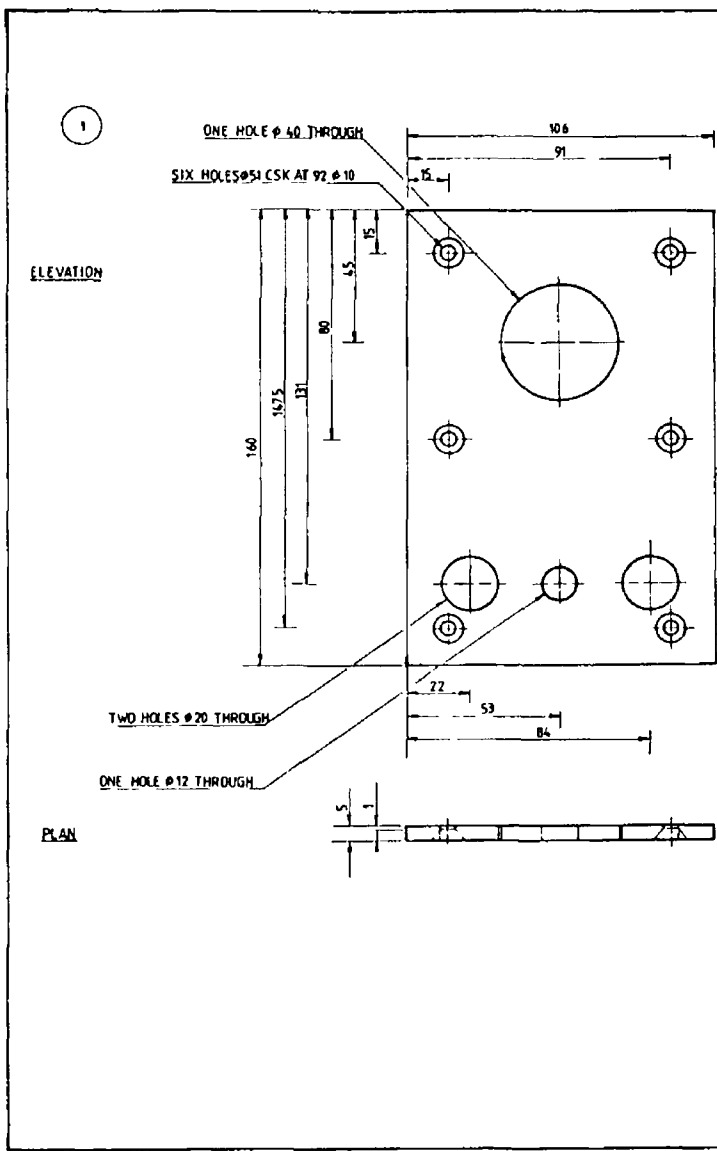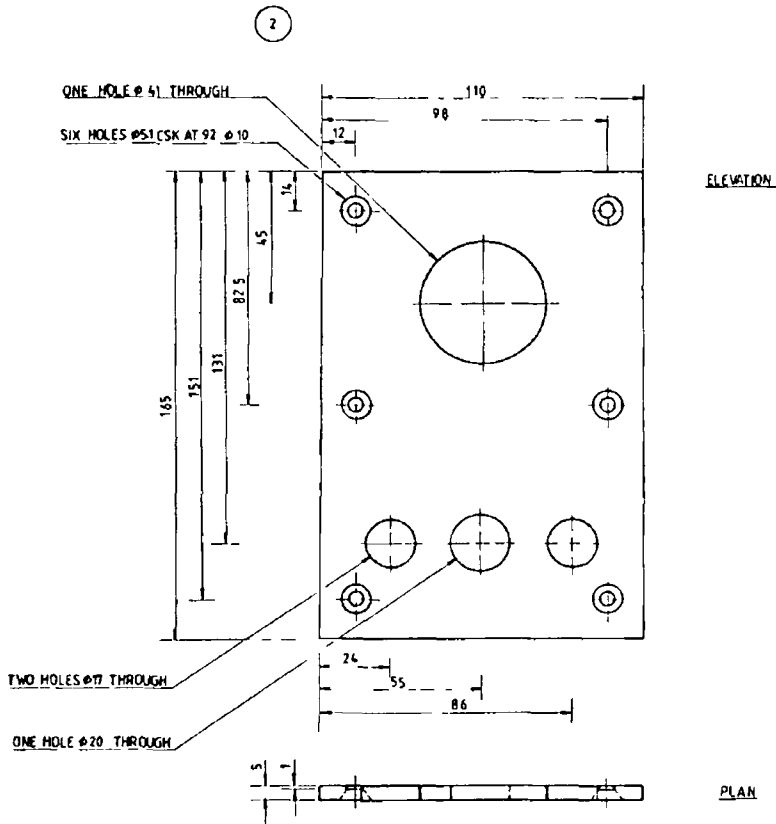
FIGURE 39

2	1	Bearing retainer	AL Alloy BS NS4 H3	01C03
1	1	Bearing retainer	AL Alloy BS NS4 H3	01C04
NO	QNTY	DESCRIPTION	MATERIAL	DRG No

DRG BY M T BHATTI	SCHOOL OF MECHANICAL
DATE 12 08 1989 TOL. 0001	AND MANUFACTURING ENGG
	DUBLIN CITY UNIVERSITY
UNIT m m	SCALE 1:1	TITLE
	BEARING RETAINERS

DRG NO   01C03 and 01C04

ELEVATION

PLAN

90

40

31

30

15

15

15

45

60

145

45

80

131

147.5

ø2.6

ø40

ø42.7

A

// 0.05 A

23

60

106

B

// 0.05 B
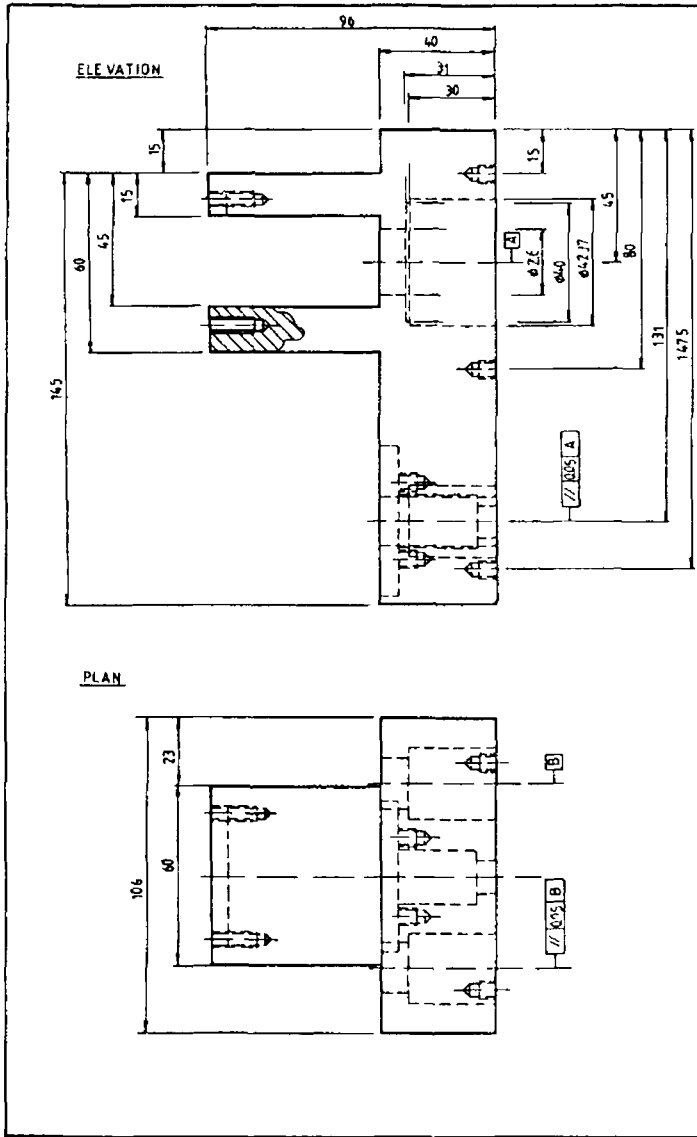
FOUR HOLES M4=7 15 DEEP
TAPPING DRILL ⌀3 3 18 DEEP
ON ⌀60 PCD EQUALLY SPACED

SIX HOLES M5 8-65 DEEP
TAPPING DRILL ⌀4 2×9 DEEP

ONE HOLE ⌀50 5 6 DEEP

ONE HOLE ⌀18 5 ×32 DEEP

FOUR HOLE M5×8 65 DEEP
TAPPING DRILL ⌀42×9 DEEP
ON ⌀35 PCD EQUALLY SPACED

ONE HOLE ⌀11 THROUGH

ONE HOLE ⌀24 K7 30 DEEP

ONE HOLE ⌀17 THROUGH

END   VIEW
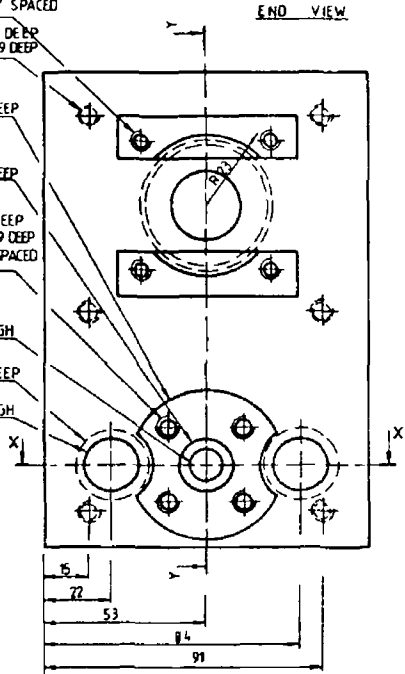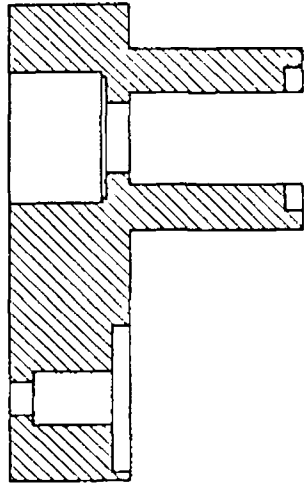
SECTION Y Y

SECTION   X X
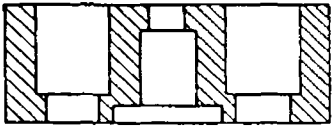
FIGURE   40

DRG BY MT BHATTI		SCHOOL OF MECHANICAL
MATERIAL AL Alloy BS HE30 TF		AND MANUFACTURING ENGG
DATE 12-08-1989		DUBLIN CITY UNIVERSITY
UNIT m m	SCALE 1/1	TITLE
QUANTITY ONE	T OL 0001	MAIN MOTOR SUPPORT UNIT
		DRG NO 01C05

SCALE 1:1

①

ELEVATION

486

30

10

20

233

403

430

470

□ 0 005 A

SCALE 1:2

PLAN

THREE HOLES ⌀6 3, C'BORE ⌀10 3 65 DEEP

FOUR HOLES ⌀12 3, C BORE ⌀18 4 12 5 DEEP

THREE HOLES ⌀10 3, C BORE ⌀16 4 10 5 DEEP

②

110 90 55 20

40 55 70

SCALE 1:1

37 70 37

37

37

70

37

0 060
0 020

⌀ 88 9

⌀ 60

FOUR HOLES ⌀5 6 C BORE ⌀9 5 1 DEEP AT 60 PCD

FOUR HOLES ⌀6 15 C'BORE ⌀10 5 5 DEEP AT 130 PCD

10 5

ONE HOLE ⌀46 AT CENTRE THROUGH

SCALE 1:1 ③

TWO HOLES ⌀M4 6 DEEP

46

20

14

6

0 018
ONE HOLE ⌀14 0 000 20 DEEP

25

⌀76 0 00
0 02

0 025
ONE HOLE ⌀15 875 0 005 26 DEEP

⌀ 26

FOUR HOLES ⌀5 2 CSK AT 97
⌀10 ON ⌀35 PCD EQUALLY SPACED

④

SCALE 1:1

ONE HOLE M10 15 THROUGH

R12 5

25

60

50

45

17 5

8

20

25

5

FIGURE 41

4	1	Nut	M Steel AISI P20	01C 12
3	1	Coupling	M Steel AISI P20	01C 06
2	1	Adaptor for gear box of ratio 18 1	Al Alloy BS HE30 TF	01C 07
1	1	The base of Y axix	Al Alloy BS HE30 TF	01C 11
NO	QNTY	DESCRIPTION	MATERIAL	DRG

ORG BY M T BHATTI	SCHOOL OF MECHANICAL
DATE 15-8-1989 TOL 0.001	AND MANUFACTURING ENGG
UNIT m m SCALE SEE DRGs	DUBLIN CITY UNIVERSITY

TITLE

Parts of MANIPULATION UNIT AROUND
AND ALONG Y AXIX (01C)

01C 06 , 01C 07 ,

DRG NOs 01C 11 and 01C12

ELEVATION

END VIEW

86
30

[A]

TWO HOLES Ø10H7 THROUGH

ONE HOLE Ø22J6 10 DEEP

ONE HOLE Ø9 30 DEEP

FOUR HOLES M3 5-45 DEEP
TAPPING DRILL Ø2.5 6 DEEP
ON 32 PCD EQUALLY SPACED

FOUR HOLES Ø16H7 16.5
15 AND 11 DEEP (SEE PLAN)

FOUR HOLES M4×7 15 DEEP
TAPPING DRILL Ø4.2 18 DEEP
ON 60 PCD EQUALLY SPACED

ONE HOLE Ø20 11.5 DEEP

ONE HOLE Ø43 3 DEEP

15
45
60
68
46
34
22
10
20

⊥ 0.05 A

①

③

FOUR HOLES Ø32 CSK AT 92 Ø6

THREE HOLES M6×1 18 DEEP
TAPPING DRILL Ø5 21 DEEP

ONE HOLE Ø8.2
THROUGH

PLAN

ONE HOLE Ø20

ELEVATION

ELEVATION

PLAN

Ø165
25
11
15
Ø16H7

[B]

60
110
90
86
55
26
20

Ø16H7
Ø10H7
Ø16.5

// 0.05 B

②

Ø42
90
45°

92°

PLAN

FIGURE 42

Ø10H7 Ø10 ⁺⁰·⁰⁰⁵ / ⁰·⁰⁰⁰   Ø22J6 Ø22 ⁺⁰·⁰⁰⁸ / ⁻⁰·⁰⁰⁵   Ø16H7 Ø16 ⁺⁰·⁰¹⁸ / ⁰·⁰⁰⁰

NO	QNTY	DESCRIPTION	MATERIAL	DRW
3	4	Washers	M Steel AISI P20	01C09
2	1	Retaining ring	AL Alloy BS HE30 TF	01C10
1	1	Motor support unit 2	AL Alloy BS HE30 TF	01C08

DRG BY M T BHATTI		SCHOOL OF MECHANICAL
DATE 13-08-1989	TOL 0.001	AND MANUFACTURING ENGG
		DUBLIN CITY UNIVERSITY
UNIT mm	SCALE 1:1	TITLE

Parts of MANIPULATION UNIT AROUND AND ALONG Y-AXIS

(01C)

DRG NO 01C08
01C10   01C09 and

ELEVATION

END VIEW

FIGURE 43

NO	QNTY	DESCRIPTION	MATERIAL	DRG
20	8	MS Counter sunk head screws	———	—
19	4	M10 Hexagone sockethead cap screws	———	=
18	6	M12 Hexagone socket head cap screws	———	=
17	2	Washers	M Steel AISI P 20	01014
16	1	Compumotor Coupling No CPG2-6	———	—
15	2	Retaining plates	Al Alloy BS HE30 TF	01013
14	2	FAG Deep grove ball bearing no 6000-2 RSR	———	—
13	1	Nut	M Steel AISI P20	01012
12	2	Washers	M Steel AISI P20	01011
11	1	Motor support unit no 1	Al Alloy BS HE30 TF	01010
10	1	Retaining rings	Al Alloy BS NS4 H3	01009
9	4	STAR Ball bushings for linear motion no 065A-120-40		
8	2	STAR Steel shaft of φ 20	Steel	01008
7	1	Lead screw M10	———	01007
6	1	Retaining ring	Al Alloy BS NS4 H3	01006
5	1	X-axis support plate	Al Alloy BS HE 30 TF	01005
4	2	Base support	Al Alloy BS HE 30 TF	01004
3	1	Main base	Al Alloy BS HE 30 TF	01003
2	2	Support plates	Al Alloy BS NS4 H3	01002
1	1	X-axis manoeuvring unit	Al Alloy BS HE 30 TF	01001

DRG BY M.T. BHATTI	SCHOOL OF MECHANICAL AND MANUFACTURING ENGG DUBLIN CITY UNIVERSITY	
DATE 06-09-1989		
UNIT m.m SCALE 1:2		
	TITLE THE BASE AND MANIPULATION UNIT ALONG X-AXIX	
	DRG NO SUB ASMBLY DRG NO 010	

ELEVATION

END VIEW

PLAN

274

5

140

481

425

240

PARALLELISM
IMPORTANT
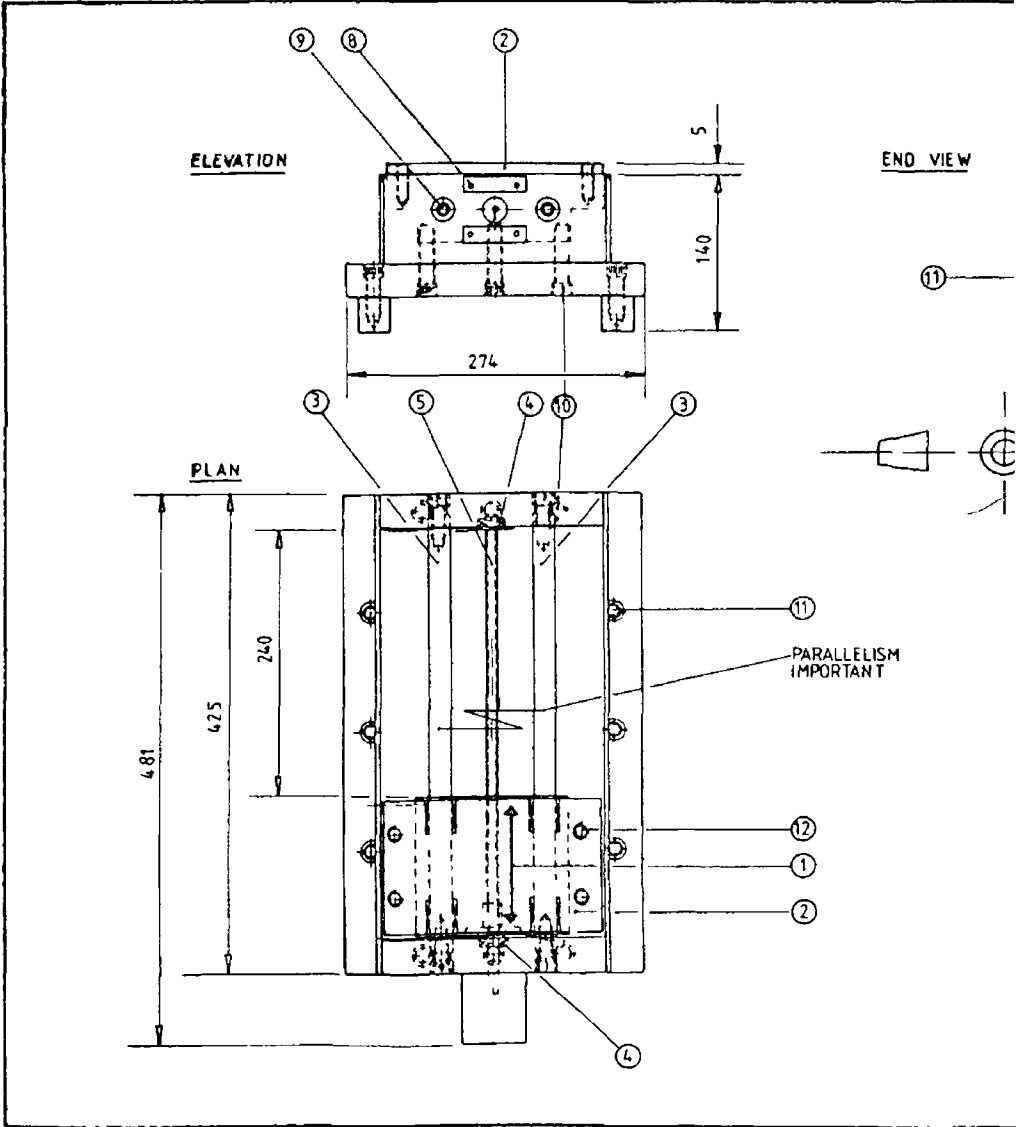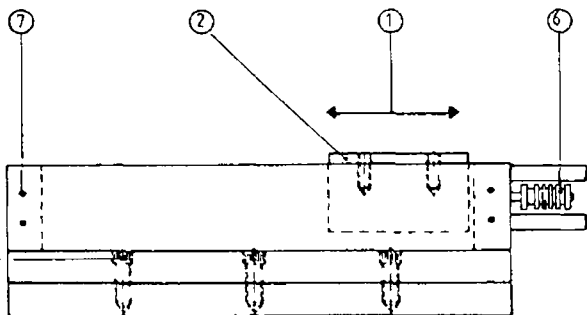
NO	DESCRIPTION
1	X-AXIX MANOEUVRING MOTION
2	MANOEUVRING PART ALONG X AXIX
3	STAR STEEL SHAFTS (TWO) Ø 30 mm
4	FAG DEEP GROVE BALL BEARINGS (TWO) NO 6000-2RSR
5	LEAD SCREW M10
6	COMPUMOTOR FLEXIBLE COUPLING NO CPG2-6
7	EIGHT COUNTER SUNK HEAD SCREWS M6
8	FOUR HOLES M4 FOR MOTOR MOUNTING
9	FOUR SOCKET HEAD CAP SCREWS M10
10	SIX SOCKET HEAD CAP SCREWS M12
11	SIX SOCKET HEAD CAP SCREWS M12
12	FOUR HOLES M12 FOR FIXING THE BASE OF Y AXIS MANOEUVRING PART

ALL DIMENSIONS ARE IN MILIMETERS

FIGURE 43a

ELEVATION

TWO HOLES ⌀21 THROUGH
FOUR HOLES ⌀28K7 30 DEEP
EIGHT HOLES M3 5 6 DEEP
TAPPING DRILL ⌀25 8 DEEP

200
148
52
15
15

67
52
47.5
30
17
10

30
45
155
170

FOUR HOLES M5 8 10 DEEP
TAPPING DRILL ⌀42 12 DEEP
ON ⌀35 PCD EQUALLY SPACED

ONE HOLE ⌀50.5 6 DEEP
ONE HOLE ⌀18.5 26 DEEP
ONE HOLE ⌀11 THROUGH

FOUR HOLES M12 1.75 35 DEEP
TAPPING DRILL ⌀10.2 THROUGH

PLAN

115
92.5
22.5
30
30

(1)

(2)

FOUR HOLES ⌀31
CSK AT 92 ⌀6

140
125
118
70
22
15

67
52
20
10

ELEVATION

ONE HOLE ⌀12 THROUGH
TWO HOLES ⌀22 THROUGH

2.5
92°

PLAN

FIGURE 44

2	2	Retaining plates	Al Alloy BS NS4_H3	01013
1	1	X axis manoeu r ng unit	Al Alloy BS HE30 TF	01001
NO	QNTY	DESCRIPTION	MATERIAL	DRG

DRG BY	M T BHATTI	SCHOOL OF MECHANICAL
DATE 16-09-1989	TOL 0.001	AND MANUFACTURING ENGG
UNIT mm	SCALE 1/1	DUBLIN CITY UNIVERSITY

TITLE

Parts of sub assembly drawing 010

DRG NOs 01001 and 01013

FIGURE 45

ELEVATION

ONE HOLE M10 x1.5 THROUGH
TAPPING DRILL Ø 8.5

FOUR HOLES Ø5.1 CSK AT 92° TO Ø10
ON Ø35 PCD EQUALLY SPACED

SCALE 1:1

THREE HOLES M12 x1.75 - 17 DEEP
TAPPING DRILL Ø 12.2 x 20 DEEP

PLAN

FOUR HOLES Ø5.1 CSK
AT 92° TO Ø10

SCALE 1:2

ELEVATION

PLAN
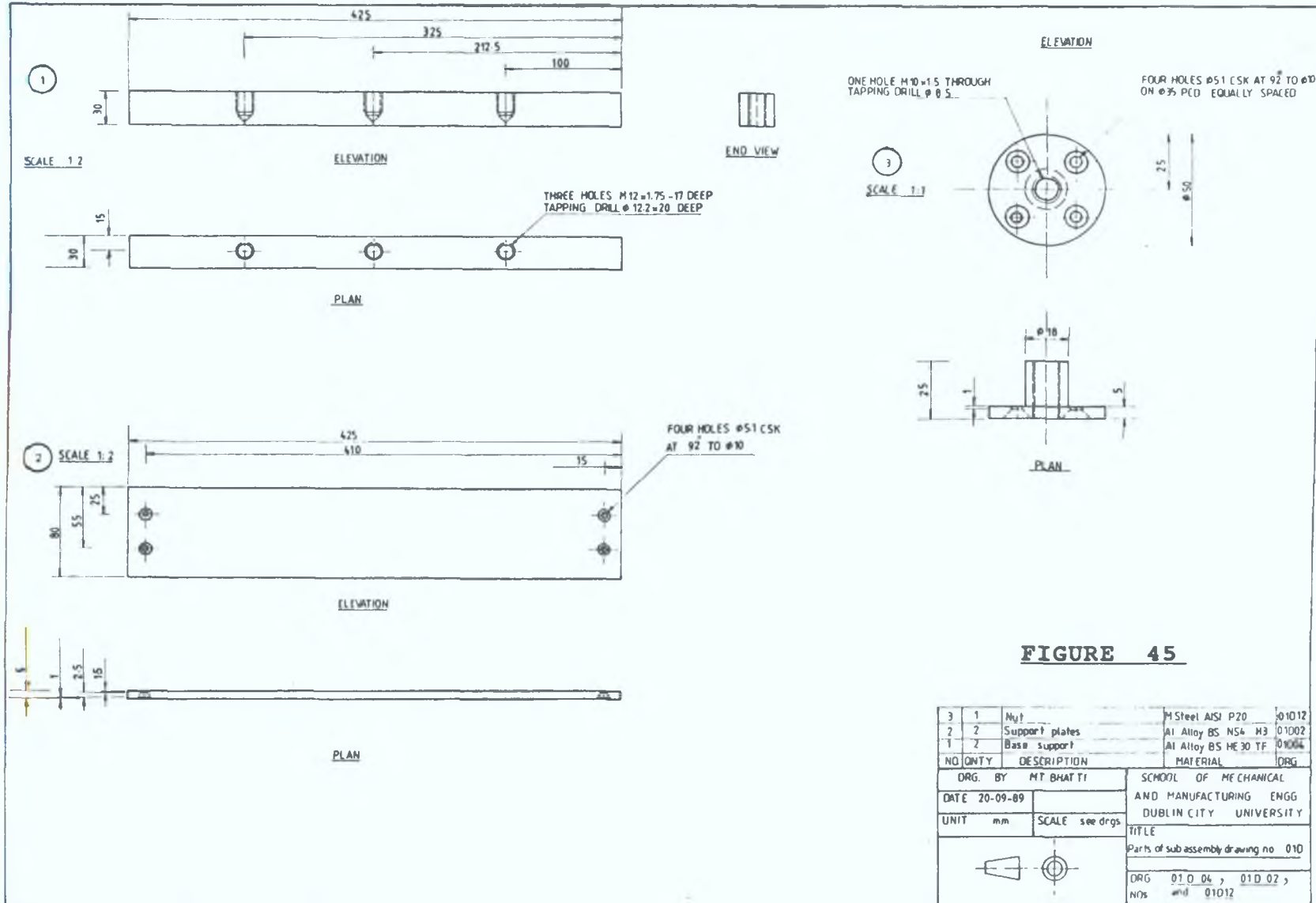
3	1	Nut	M Steel AISI P20	01012
2	2	Support plates	Al Alloy BS NS4 H3	01002
1	2	Base support	Al Alloy BS HE 30 TF	01004
NO	QNTY	DESCRIPTION	MATERIAL	DRG

DRG. BY MT BHATTI	SCHOOL OF MECHANICAL
DATE 20-09-89	AND MANUFACTURING ENGG
UNIT mm SCALE see drgs	DUBLIN CITY UNIVERSITY

TITLE
Parts of sub assembly drawing no 010

DRG NOs 01 0 04 , 01 D 02 , and 01012

SCALE 1:2

ELEVATION

END VIEW

PLAN

ELEVATION

END VIEW

FIGURE 46

PLAN

SIX HOLES ⌀12 3 C BORE ⌀ 18 5 12 5 DEEP

SIX HOLES ⌀12 3 C BORE ⌀ 18 5 12 5 DEEP

DRG BY MT BHATTI		SCHOOL OF MECHANICAL AND
DATE 17 8-89	TOL 0.005	MANUFACTURING ENGG
		DUBLIN CITY UNIVERSITY
UNIT mm	SCALE 1 2	TITLE:—
MATERIAL AL ALLOY BS HE30TF		HAIN BASE
		DRG NO 01 D03

164
150
117
102
87
54
40

① ELEVATION

ONE HOLE ⌀22J6×2 DEEP

FOUR HOLES M5 8 6 DEEP
TAPPING DRILL ⌀42 8 DEEP

ONE HOLE ⌀9 12 DEEP
ONE HOLE ⌀20H7 13 AND 12 DEEP (SEE PLAN)

ONE HOLE ⌀16 H7 THROUGH

80
63
55
48
33
25

FOUR HOLES M3 5 6 DEEP
TAPPING DRILL 25 8 DEEP

ONE HOLE ⌀20 9 DEEP

END VIEW

THREE HOLES M12 175 30 DEEP
TAPPING DRILL ⌀102 ×34 DEEP

PLAN

30
15
204

50
40
10

② ELEVATION

10
40
50

FOUR HOLES ⌀51 CSK AT 92 TO ⌀10

ONE HOLE ⌀20 THROUGH

FIGURE 47

PLAN

05
25
92

⌀22J6 ⌀22 +0.008 0.005
⌀20H7 ⌀20 +0.021 0.000
⌀16H7 ⌀16 +0.018 0.000

2	2	Retaining rings	Al Alloy BS NS4 H3	01D06
1	1	X-axis supporting plate	Al Alloy BS HE30 TF	01D05
NO	QNTY	DESCRIPTION	MATERIAL	DRG

DRG BY	M T BHATTI
DATE 21-8-1989	TOL 0.001
UNIT mm	SCALE 1 1

SCHOOL OF MECHANICAL
AND MANUFACTURING ENGG
DUBLIN CITY UNIVERSITY

TITLE
Parts of sub assembly drawing 010

DRG NOs 01D05 and 01D06

425

405

375

10

① ELEVATION

Φ 6 35   Φ 8j6   M 10   Φ 8j6

END_VIEW

399

394

② Φ 70   5   TWO HOLES M10 15 30 DEEP

ELEVATION   **FIGURE   48**   END_VIEW

Φ16h6 Φ16 $^{0000}_{0009}$ Φ8j6 Φ8 $^{0087}_{0002}$

2	2	STAR Steel shafts of Φ20	————	01008
1	1	Lead screw M10	————	01007
NO	QNTY	DESCRIPTION	MATERIAL	DRG

DRG BY M T BHATTI	SCHOOL OF MECHANICAL
DATE 20-09 1989	TOL 0.001	AND MANUFACTURING ENGG
		DUBLIN CITY UNIVERSITY
UNIT mm	SCALE 11	TITLE
		Parts of sub assembly drawing no 010
		DRG NOs 01008 and 01007

FIGURE 49

ONE HOLE ⌀20 9 DEEP

FOUR HOLES M3 5 5 DEEP
TAPPING DRILL ⌀25 7 DEEP

TWO HOLES ⌀20H7 12 AND
13 DEEP(SEE PLAN)

TWO HOLES ⌀16H7 THROUGH

FOUR HOLES M4 7 15 DEEP
TAPPING DRILL ⌀33 16 DEEP
ON ⌀60 PCD EQUALLY SPACED

ONE HOLE ⌀22J6 7 DEEP

ONE HOLE ⌀9 30 DEEP

FOUR HOLES M5 8-6 DEEP
TAPPING DRILL ⌀42 8 DEEP

ELEVATION

PLAN

THREE HOLES M12 x1.75 30 DEEP
TAPPING DRILL ⌀102 34 DEEP

END VIEW

ELEVATION

ONE HOLE ⌀102 THROUGH

END VIEW

⌀16H7=⌀16 0.018 / 0.000   ⌀22J6 ⌀22 0.008 / -0.005   ⌀20H7 ⌀20 0.012 / 0.000

2	4	Washe s	M Steel AISI P20	01011 & 14
1	1	Motor support unit 1	Al Alloy BS HE30TF	01D 10
NO	QNTY	DESCRIPTION	MATERIAL	DRG NO

DRG BY	M T BHATTI		SCHOOL OF MECHANICAL AND MANUFACTURIG ENGG DUBLIN CITY UNIVERSITY
DATE 20-09 89	TOL	0 005	
UNIT mm	SCALE	11	TITLE

Parts of sub assembly drawing no 01D

DRG NOs 01D10, 01D11 and 01D14

FIG. 1. THE FOUR AXES PRECISION MANIPULATOR

CHAPTER THREE

INTERFACING

3.1. AN OVERVIEW OF THE INTERFACING SYSTEM

The successful implementation of micro-computer in a control application requires appropriate interfacing of the device / machine tool with the micro-computer. The machine tool in this case is the four axes manipulator, to generate 3-dimensional surfaces in polystyrene model material by simulated WEDM process.

The interface used in this network has two main elements in between the micro-computer and AC brushless servo motors. These are known as PC23 indexer and KS-drive. **Figure 50** shows a full schematic diagram of the interfacing system including additional facilities developed.

Each of the prototype indexers which have been used in this research work can control three axes independently and simultaneously. It is designed to be inserted into an IBM micro-computer (PC, XT or AT) or compatable. The PC23 indexer uses a 16 bit processor to manage the control of three motor axes. Two PC23 indexers and four KS-drives (one for each motor) were used to generate the appropriate motion to describe the shape.

The PC23 indexer receives acceleration, velocity, position and direction information from the micro-computer based software. The on board micro-processor uses this information to generate motion profile command signals for the KS-drives **(95)**. The KS-drive accepts these digital "step" pulses from the indexer, at controlled rates up to 5000,000 steps per second, and the internal drive logic and power amplifiers set and maintain output current levels to the AC servomotor windings **(96)**

The additional facilities of the PC23 indexer like trigger inputs and programmable outputs have been utilized by designing a Programmable Voltage Regulator **(PVR)** circuit, which controls the voltage in the cutting wire

3.2. PC23 INDEXER

The PC23 indexer consists of two parts, which are the main circuit board and the adaptor box. The main circuit board is incorporated inside the microcomputer and connected to the adaptor box. The adaptor box is outside the computer and has all connections to the KS-drives and other devices.

These two PC23 indexers are set at two different addresses (not sharing with any other peripheral); one is set at **300** hex (768 decimal) and the other at **310** hex (784 decimal) in the I/O bus of the Prompt computer (IBM

compatable) with 20 MB hard disk, a floppy drive and a 640 KB RAM. A PC23 system diagram is shown in **figure 51**, and its specifications are given Appendix **B1**.

Each PC23 indexer occupies four address locations on the I/O bus, 300 hex through 303 hex for indexer one and 310 hex through 313 hex for indexer two. The control and status registers are at the odd address locations (301 and 311 hex), and data registers are at even address location (300 and 310 hex). Each PC23 main circuit board has eight micro-switches, allowing to set any convenient address. These are "negative true", meaning that any switch in position marked "ON" has a binary value of zero. Switches kept at "OFF" position have a non-zero binary value. The sum of binary values of switches one through eight is the board's base address. Values assigned to eight switches and to both indexers are given in **table 2**.

Switch No.	Address bit	Binary Value (off) Decimal	Hex	PC23 No. 1	PC23 No.2
8	2	4	4	ON	ON
7	3	8	8	ON	ON
6	4	16	10	ON	OFF
5	5	32	20	ON	ON
4	6	64	40	ON	ON
3	7	128	80	ON	ON
2	8	256	100	OFF	OFF
1	9	512	200	OFF	OFF

Table 2   Address select switch values of PC23 indexer one and two.

Each of the adaptor boxes has three 25-D pin connectors, called **MOTOR DRIVER,** **ENCODER** and **AUXILIARY** for each axis. All signals connected to the adaptor box

are optically isolated from the micro-computer, KS-drives and other devices. To power up both these adaptor boxes so as to transmit and receive all TTL signals in this isolated part of the circuit, an external,fixed power supply of 5 VDC at 10 Amperes is connected to one of the AUXILIARY connector's pin (numbers 23 (+ve) and 21 (-ve) on each indexer).

The pulses received by the indexer from the micro-computer are transmitted to the KS-drive via appropriate **MOTOR DRIVER** axis number (1,2 or 3) to control acceleration, velocity and to set direction or to de-energize the motor.

The **ENCODER** connector, accepts position feed back signals from an optional incremental encoder and provides the power to the same. The encoder has not been used in the present **CNC** system. The reason for this is that the performance of this interfacing system has been observed as being very high, and some of the encoder features in this application are solved by software. The optional encoder may be used to give a more reliable positioning tracking system. It's use would also improve the closed loop operation between the indexer and motors. The optional **incremental encoder** position tracking can be used to:

(1) Provide closed loop positioning for improved accuracy by comparing steps sent to motor and step responses coming from the encoder.

(ii) Dynamically hold an encoder referenced position. Usually at the end of a move in the encoder step mode, it's position is not monitored any more to maintain it's position. If any external force causes the load to move, the indexer will not take care of it. By programming, an axis can be configured to resist such external forces. Then, if external forces cause the encoder position to change, the indexer will attempt to correct and maintain the load position.

(iii) Detect motor stall: The number of encoder steps received by indexer are repeatedly compared against the number of motor steps going out for any move to verify that no gross discrepency exists. If the encoder position deviates excessively from the expected position in the course of the move, then the indexer will assume the motor has stalled. An encoder can also be programmed to compensate for the backlashes in the geartrain and screws

(iv) It is possible to programme all axes to stop moving in the event of any one of the axes stalling or losing it's position.

3.3. INPUT AND OUTPUT SIGNALS OF THE PC23 INDEXER

All input and output signals, which could be made a logical extension to the adaptive control in this CNC system, are connected to the **AUXILIARY** connector.

An **AUXILIARY** connector provides connections to load related switches and other functional sensors to enhance position and process control. Appendix **B5** shows I/O wiring diagram of an AUXILIARY connector and pin assignment of the PC23 indexer. Each AUXILIARY connector for an axis has two programmable outputs, two trigger inputs, one **CW** limit, one **CCW** limit and one **HOME ENABLE** input. It means that on both indexers there are **12** programmable outputs, **12** trigger inputs, **6** CW limits, **6** CCW limits, and **6** HOME ENABLE inputs.

Any one of the 12 programmable outputs may be turned "ON" or "OFF", or during the execution of sequential operations to signal or control external devices. An indexer command "O" may be used for this purpose. Any one of the 12 trigger inputs can be connected to external sensors or other signal sources to provide the indexer with information on external conditions. The execution of sequential operations can be synchronized by these conditions or events. The indexer can be programmed to wait until one or more input switches to a desired state. The "TR" and "TS" indexer commands can be used to carry out these operations.

The CW and CCW limit inputs can also be used to protect the limited travel mechanism from over travel. 'Normally closed' switches can be typically mounted close to the end of the travel to provide an emergncy stop signal to the indexer. When an axis receives a limit signal

corresponding to the direction the motor is moving, it stops the motor. The concerned indexer commands for CW and CCW limits are "RA", "LA" and "LD".

The HOME ENABLE input function may be used to establish a home reference position (zero position). A 'normally closed' switch may be mounted at a reference position. If the switch is mounted at the end of CCW travel, then all the position coordinates will be positive. If however, the switch is mounted at the middle of travel then the position coordinates will be half positive and half negative. Any axis may be instructed to move the motor to a home position using a single command and report the distance between the original position and home position. The supporting commands for this input are "GA", "GH", "RC" and "FS".

The optional encoder, CW limit, CCW limit, and HOME ENABLE facilities have not been utilized in the present system. Some of the features offered by these facilities are solved through software generated. CW, CCW and HOME ENABLE facilities are overcome by knowing the maximum linear and rotational distance limits and geometry of profile to be generated.Backlashes in gear boxes and screws are also compensated through software.

3.4. PROGRAMMING PC23 INDEXER

Programming the PC23 indexer is independent of the programming language. The control program only needs to have a means of reading data from Output Data Buffer **(ODB)** and writing indexer commands to Input Data Buffer **(IDB)** at the **base address** of the indexer. This transfer of characters from **ODB** and **IDB** takes place one character at a time, because these registers can hold only one character (one eight bit 'Byte'). The transfer of string commands to the PC23 indexer and it's responses back to computer involves handshaking between them. It means each character transfer requires that the sender notify the receiver that the character is ready, and that the receiver notify the sender that the character have been received. PC23 has two special bytes for this purpose known as Control Byte **(CB)** and Status Byte **(SB)**. Where each **CB** and **SB** is eight bits with special meanings. For successful dialog between PC23 indexer and micro-computer, the programmer must know the meaning of each bit of the **CB** and the **SB** regardless of which programming language is being used.

The interface program writes the CB and reads the SB from the register at one digit above base address (i.e. **base address +1**). The CB allows certain conditions to be set and the SB reports other conditions Signalling the PC23 involves "setting" or "clearing" control bits which means forcing them to a binary value of one or zero respectively. In the PC23 indexer, the **ODB** and the **SB** are

read only registers. The **IDB** and the **CB** are write only registers **(95)**. The definition of each bit of the **CB** **is described below :**

Bit 0 : When set indicates that the Binary Mode of data input for **TD** mode of contouring is under way.

Bit 1 : Unused.

Bit 2 : When set, causes the PC23 Watchdog Timer to time out and stop. When the timer stops, it forces a hardware reset. The reset condition may be cleared by cycling power or restarting the timer.

Bit 3 : When set, ╱ tells the PC23 that the interrupt signal to the computer has been noted and is no longer needed.

Bit 4 : When set, tells the indexer that a command character has been put into the **IDB.** The Indexer then clears Bit 4 of the **SB** to indicate that the **IDB** is unavailable. The indexer reads the character in the **IDB,** and then sets bit 4 of the **SB** to indicate to the host that the **IDB** is again ready for a new character.

Bit 5 : Restarts the Watchdog Timer. It must first be

cleared, then the timer will start up when bit is set again. This bit should never be toggled unless the timer has timed out.

Bit 6 : Reset the hardware interrupt latch and thus the interrupt output. The interrupt output can not be reset unless the interrupt is first acknowledged with bit 3 above. These bits should be cleared during reset or interrupt acknowledge.

Bit 7 : When set, tells the indexer that a response character, previously placed by the host, and a new character may be placed in Output Data Buffer.

Definition of **Status Byte (SB) is described below** :

Bit 0, 1, and 2 : Indicates whether the motors for the three axes are moving. At the beginning of any move, the appropriate bit is cleared. Specifically these bits indicate whether or not the indexer is sending step pulses to the drives.

Bit 3 and 4 : Are set when their corresponding data buffer is ready; bit 3 is set when the **ODB** contains an output character for the host, signalling the host to read the information it contains, bit 4

is set when the **IDB** is ready, telling the computer it may write a character to a character to the **IDB**.

Bit 5 : When set, tells PC that the watchdog timer of the PC23 has timed out, possibly indicating an internal failure from which it cannot recover. The only way to clear this bit is to reset the indexer.

Bit 6 : Indicated to the host that a conditional interrupt has been "armed" and that the condition has occured.

Bit 7 : Reserved.

For transfering these indexer commands and getting responses back to the host computer, two special subroutines have been built in all the concerned software for both indexers, which allows the successful motion control. These two subroutines are called as "output driver" and "input driver" for sending and receiving characters respectively. The command character sent to PC23 is assigned to a string variable **CMD$** and responses received back to host computer are assigned to a string variable **ANSWER$**. Before we send or receive any character, PC23 needs to be "reset", that means to keep all the bits of SB and CB ready for any kind of transfer. This process is done by assigning different hexadecimal numbers to the

appropriate variables. These variables are used by their Logical ANDing throughout the "resetting", "input driver" and "output driver" subroutines.

These functional subroutines are developed in the GWBASIC programming language. The most important requisite for programming the PC23 indexer is to have knowledge of string handling in the programming language to be used. The PC23 indexer has approximately eighty commands, which can be used to specify different conditions and operating modes within the control programme, to control the motion and get status information back to the host computer. Better motion control and responses from the indexer lies in the selection of suitable commands for any particular shape. A summary of the PC23 indexer commands is given in Appendix **B8**.

For accurate speed control, each axis needs to know what resolutions it's motor has; and the settings of steps / revoluion on the KS-drive and the PC23 indexer must match. The standard motor resolution setting for all the axes on PC23 indexer is 25000 steps/revolution. Whereas, KS-drives for motors KS210 and KS220 are configured in the range of 1000 to 16,384 steps / revolution. At the moment all KS-drive settings are kept at 5000 steps /revolution. It means the motor will run five times as fast as indexer settings. On the indexer "MR6" command is used to match the motor indexer motor resolutions of 5000 steps/rev. with the KS-drive resolution. The "MRn" command also

controls step pulse width and velocity range. **Table 3**
shows the range of steps that can be achieved by "MRn"
command.

Motor Resolut-ion	Frequency Range(Hz)	Velocity Range (RPS)	Pulse W. (micro Sec.)	PC23 Command
200	1.018 - 32000	.01 - 160	15	MR0
400	1.018 - 32000	.01 - 80	15	MR1
800	2.036 - 64000	.01 - 80	7.5	MR2
1000	3.052 - 100000	.01 - 100	4	MR3
1600	3.052 - 96000	.01 - 60	4	MR4
3200	7.629 - 250000	.01 - 80	2	MR5
5000	15.259 - 500000	.001 - 100	1	MR6
6400	15.259 - 512000	.01 - 80	1	MR7
10000	15.259 - 500000	.001- 50	1	MR8
21600	15.259 - 496800	.001- 23	1	MR9
25000	15.259 - 500000	.001- 20	1	MR1
25400	15.259 - 508000	.001- 20	1	MR1
36000	15.259 - 504000	.001- 14	1	MR1
50000	15.259 - 500000	.001- 10	1	MR1
50800	15.259 - 500000	.001- 10	1	MR1
4096	15.259 - 500000	.01 - 120	1	MR1
12800	15.259 - 500000	.001- 40	1	MR1
25600	15.259 - 500000	.001- 20	1	MR1
12500	15.259 - 500000	.001- 40	1	MR1
16284	15.259 - 500000	.001- 30	1	MR1

Table 3   **Shows motor resolution frequency   ranges,
velocity ranges   and pulse widths with
corresponding indexer "MR" command.**

3.5. PROGRAMMING STRUCTURE OF THE PC23 INDEXER

Programming structure of the PC23 indexer can be
classified into following three stages **(95)** in order of
importance :

(i) Resetting PC23   indexer.

(ii) Sending a command character to PC23 indexer (Output

- 137-

driver subroutine), and

(iii) Receiving a character from the indexer (input driver subroutine).

(i) **RESETTING THE PC23 :**

1. Write 64 Hex to the Control Port (Board Address +1).

2. Read the Status Port (Board Address + 1) until (the status byte AND 20 Hex) = 0

3. Write 40 Hex to the Control Byte (Board Address + 1).

4. Read the Status Port (Board Address + 1) until (the status byte and 7F Hex) = 17 Hex

5. Write 60 Hex to the Control Port (Board Address + 1).

6. Write 20 Hex to the Control Port (Board Address + 1).

(ii) **READING A CHARACTER FROM THE PC23**

1. Initialize the ASCII variable to null (0).

2. Read the Status Port (Board Address+ 1) until (Status Byte AND 8 Hex) > 0.

3. Read the Data Port (board Address) into the ASCII variable.

4. Write E0 Hex to the Control Port (Board Address + 1).

5. Read the Status Port (Board Address + 1) until (the SB AND Hex) = 0.

6. Write 60 Hex to the Control Port (Board Address + 1).

(iii) WRITING A CHARACTER TO THE PC23

1. Convert the character to ASCII. This may not be necessary in some proramming languages such as C. (Except for Binary Input mode for axes in the TD mode).

2. Read the Status Port (Board Address + 1) until (the Status Byte AND 10 Hex) > 0.

3. Write the ASCII character to the Data Port (Board Address).

4. Write 70 Hex to the Control Port (Board Address + 1)

5. Read the Status Port (Board Address+ 1) until (the Status Byte AND 10 Hex) = 0.

6. Write 60 Hex to the Control Byte (Board Address + 1).
   Note : AND = Bitwise logical and.

All the Hex numbers are assigned to variables including the addresses for indexer one and indexer two to a **address1%** and **address2%** integer variable. Once these three stages are developed, then operation of manipulator only needs a programme of instruction, which describes all the geometrical criteria of the profile to be generated. These three stages of PC programming structure allow all the geometrical entities to be handled in a sequential way.

3.6. MOTION CONTROL OF PC23 INDEXER

All applications of an indexer axes involve either

movement of a motor to a precise position (number of steps) or movement of the motor at a prescribed velocity (revolutions/second). Output control for both position and velocity can be controlled with a high degree of precision. For that purpose, the PC23 indexer offers three principal modes of operation known as **Normal** mode, **Alternating** mode and **Continuous Mode**, which can be selected by **MN, MA** and **MC** commands respectively.

In **Normal Mode**, the indexer drives the motor to a specified position at a specified velocity and accelerates and decelerates at a specified rate. All three modes need acceleration and velocity and **Normal** and **Alternating** Modes need distance parameters. In continuous mode only acceleration and velocity parameters are required, then the Go command , will start motion continuously until the stop **"S"** or the kill **"K"** command is issued. Commands like change direction **"H"**, or shut down motor **"ST"** are inappropriate. This mode may be switched to Normal or Alternative by issueing **MN** or **MA** commands after stoping the motor by **"S"** or **"K"** commands.

In **Alternative mode**, the specified parameters of acceleration **"A"**, velocity **"V"**, and distance **"D"** and the Go **"G"** command cause the motor shaft to rotate to the commanded position corresponding to the specified distance parameter value, set by **"D"** command. The motor shaft then retraces its path back to the start position. The shaft will continually move between the start position and the

commanded position until a Stop "S" command is received by the indexer. Then the motor will complete the cycle and stop at the start position. The motor can be immediately stopped by using the "SSD0" command. The Normal mode is further subdivided into two sub-modes known as **Absolute** and **Incremental** modes, which can be switched on by **MPA** and **MPI** commands respectively. In Absolute mode all the motor moves are referenced to absolute zero position. The incremental mode makes each next move from present motor reference position.

The **normal mode** is more suitable for the simulated WEDM process. The distance parameter is defined in terms of motor steps. The linear and rotary distance in millimeters and degrees must be translated into motor steps by keeping an account of the pitch of the lead screw and the gear ratios. The accelaration and velocity is defined in revolutions/sec^2 and /sec respectively. Once indexer communication is established, and proper motion mode and move parameter values are assigned to appropriate indexer commands, then only a go "G" execution command is needed to initiate motor motion. PC23 indexer commands are preceeded by number 1, 2 or 3, identifying which axis to execute the commands. Each axis buffer can hold 1000 command characters including spaces.

For example, if we want to move motor two with an acceleration of 0.1 rev./sec.^{2} and a velocity of 0.2 rev/sec. through a distance of 10 mm in the CW direction

and if the indexer is set at 5000 steps/rev., and the KS-drive is also set at the same resolution and the mode selected is absolute then the number of motor steps is caculated as follows

10 mm (linear distance) x 5000 (steps/rev) / 2 mm (pitch of lead screw) = 25,000 motor steps.

Then the command to indexer will be

1MN 1MPA 1A0.1 1V0.2 1D-25000 1G

3-dimensional complex shapes can be machined by generating the commands required, dividing a desired position contour into numerous short straight line segments. A list of the pre-calculated distances, velocities and accelerations for any particular shape from end point to end point is fed to the PC23, and is essentially moved to "connect the dots". Smoother curved contours can be achieved if a larger number of segments are used to approximate the curve. To do so, it is necessary to shorten the update time, to maintain a fairly constant ratio between the update time and the segment lengths. This ratio translates into motor acceleration and velocity.

The trick to initiating multiple axes motion lies in getting all the axes to start, finish acceleration, start deceleration, and stop in a synchronized motion.

3.7. SYNCHRONIZED OPERATIONS

It can be difficult to get two or more axes to execute some function at the same time without the use of global synchronized commands. To do so, it is necessary to halt execution of commands, until all axes are ready to move in synchronized way. The PC23 indexer offers two ways to generate the halt, and a subsequent synchronized start using PC23 pause commands. The synchronization can be implemented under software control, or under control of a hardware signal. This signal may be generated either externally or by the PC23 indexer itself (95). Both the synchronized operations are described below

3.7.1. SOFTWARE CONTROLLED SYNCHRONIZATION

The axes involved may be instructed to pause and wait for the computer to clear the pause. The pause "P" command can be included in the sequence of commands for participating axes before the go "G" command. Once this sequence of commands is received by all axes, then continue "C" command can be sent to each axes buffer to initiate execution. When the "C" command is individuallly directed to participating axes, to clear the pause, the timing of the command communications can render the actual execution timing indeterminate. If new motion parameters are involved, the PC23 must calculate move constants prior to execution. This result in even greater uncertainty as

to the execution time. The load and go functions and the load commands "I" and "IC" may be used to eliminate this uncertainty.

As the PC23 command processor is constantly switching sequentially from one axis to another to handle command processing. This time sharing process switches every two milliseconds. If it is necessary to carry out a function on two axes then the time difference involved in it's execution on the two axes will be at least two milliseconds (95). To generate any complex profile there will be a large number of buffered commands for small segments for each axis. The time difference will affect the accuracy of the geometry of the profile. The probability of inaccuracy increases when using two PC23 indexers. This means that the total time difference between the first axis of the first indexer and the first axis of the second indexer will be atleast six milliseconds for each point on the profile. Because of this, the process of issuing Pause "P" and Continue "C"commands for implementing the synchronization is not adopted.

The method adopted is, firstly to send all of the pre-calculated move parameter values and "I" commands to each motor axis buffer to both indexers. When all these commands are received by the indexers then by sending a global command "G123" (move all three motor axes on indexer one) and "G1" (move axis

one 'fourth motor' on indexer two). As the motor motion is initiated, the computer sends all the next move parameter values to the corresponding axes buffers. The control program then starts reading the status bits on both indexers for the initially sent move parameters to make sure that they have achieved the desired position and all the motors are stopped and are ready for this last move. Then the computer again sends "G123" and "G1" commands to both the indexers to make this move. This process is continuously repeated until all the small segments are machined in this synchronized fashion.

With the global command "G123", each axis starts within 150 micro seconds of one another. Beside this, machining of a new segment of the profile can only be started when the current move is finished.

3.7.2. EXTERNAL SIGNAL CONTROLLED SYNCHRONOZATION

This kind of synchronization makes use of trigger inputs available on the indexers. The axes involved can be programmed to pause for one or more trigger inputs to clear a trigger pause. The trigger input signals used to initiate execution may be generated externally by sensors or by other signal devices in a process control situation. For this purpose the "TR" (wait for trigger input) command can be included in the sequence of commands for each of these axes. Each

of these axes can be instructed to wait for the same trigger input signal to execute the commands in synchronized way. Otherwise, any one of the indexer's of the PC23's six programmable outputs may be fed back into a trigger input, which is designated as the synchronization input. In this configuration, one axis is designated as the synchronization to controller. For both of these external signal controlled synchronization methods it is necessary to include some or all of **"TR"**, **"TS"** (test status of trigger inputs) and **"O"** (set programmable outputs) commands in the sequence of commands for each of the axis.

These trigger inputs and programmable outputs have been utilized to design a Programmable Voltage Regulator **(PVR)**.

3.8. PROGRAMMABLE VOLTAGE REGULATOR (PVR) CIRCUIT DESIGN

The main reason for designing this PVR circuit is to allow the microcomputer to control the voltage in the cutting wire at four different adjustable values, and let the intelligent software to take new steps by continuously monitoring external conditions in this simulated **WEDM** process. This has been done by making use of available programmable outputs and trigger inputs on one of the indexers.

This PVR circuit together with the trigger input facility interfaced to indexer and microcomputer is shown in **figure 52.**

The **PVR** circuit can be divided into two major parts, the **LM-338** voltage regulator and other controlling parts. The voltage regulator LM-338 is the main part of this circuit. This is an adjustable 3-terminal positive regulator, capable of supplying in excess of 5 amperes, with an output range of 1.25 to 32 volts. The LM-338 voltage regulator chip has thermal overload protection and a safe area protection for it's internal elements. The technical data and specifications of the LM-338 voltage regulator are shown in Appendix **B4** . Other parts of the PVR circuit are the control parts formed by four potentiometers and five general purpose NPN transistors. The potentiometers have values of 0 to 50 k.Ohms with a 10% tollerance. The two capacitors are used as well in the PVR circuit to smoothout the transitory effects during switching of the circuit. A DC power supply unit is connected to the PVR. It can supply 0 to 30 volts and 0 to 5 amperes. It is protected against excess current. The five transistors are connected to programmable outputs on indexer number one.

The total voltage in the cutting wire is the addition of constant voltage established between A and B (see figure 52) by LM-338 voltage regulator and the voltage generated by the constant current in the selected potentiometer.

$$Vt = V1 + (\text{Iad} \times Rpt)$$

Where   **Vt** = Total voltage in cutting wire.

V1 = Constant voltage given by LM-338 voltage regulator (1.25 volts).

Iad = Constant current given by the LM-338 voltage regulator through it's adjustable terminal (45 micro amperes)

Rpt = Resistance value of one of the selected potentiometers (0 to 50 k.ohms)

The values of **Rpt** can be changed by tuning any one of the selected potentiometers, which will result in a new total voltage value. This total voltage value can be in the range of 1.25 to 32 volts with a current of 0 to 5 amperes. At the moment these four total voltage values are kept at 4.5, 5, 5.5 and 6 volts. The fifth transistor can give a constant total voltage value of 1.25 (V1) volts.

Controlling the voltage in the cutting wire from the computer based software involves sending a TTL signal via one of the programmable outputs, to any one of the five transistors, which work like switches. Only one transistor can be closed at any one time. By closing another transistor, the total output voltage for the corresponding potentiometer will change.

One, 'normally opened' micro-switch is also connected to the auxiliary connectors trigger input number 3 on indexer number one. This micro-switch is mounted on the wire cutting unit **(See figure 28 or 28a, drawing 01A)**, which is always in touch with tension spring. One end of

the cutting wire is fixed on this tension spring and other end is rigidly fixed on the base of wire cutting unit. The pre-travel distance of the micro-switch is **1.3 mm.** The tension spring maintains the tension on the cutting wire, whereas the wire cutting unit **(figure 28, drawing 01A)** keeps the wire perfectly vertical.

If during execution of programme to generate a shape in polystyrene model material, the voltage in the cutting wire is not sufficient to match with the feed rate of workpiece, then it will cause increased tension on cutting wire, which is perfectly held at 90 degrees. This increased tension will cause the micro-switch to be closed. This closed micro-switch will send an immediate TTL trigger input signal to the indexer, which can be read by the computer based software after each small segment generation by an indexer command **"TS"**. As soon as this trigger input number three is read by the computer, it will firstly execute "multiple axes stop" on both the indexers and a programmable output to transistor number five to bring voltage at minimum value of 1.25 volts, so that no further machining can occur. Secondly, the computer retraces all the motion paths until the pre-travel distance of micro-switch (1.3 mm) is acheived and the wire is in a perfectly vertical position. After this, the program asks the user to increase the power in the cutting wire or to reduce the workpiece feed rate than those pre-waiting in the earlier stage. This facility applies until all the profile is completely generated.

3.9. THE KS-DRIVE

The KS-drive is a complete brushless servopositioning system. It consists of brushless servomotor, a brushless feedback and microprocessor based closed loop drive amplifier. The KS-drive is manufactured by the Parker Computor Corporation.

The KS-drive accepts digital STEP and DIRECTION inputs to control position and velocity. The on-board microprocessor monitors both the pulse inputs from the indexer and the resolver feedback from motor shaft and then determines the proper current levels to apply to the motor. The resolver feedback used on KS-drive can be programmed between 1000 to 16,384 steps/revolution by using CMR command through the RS-232 interface and is saved in EEPROM memory. Presently, all four motors are set at 5000 steps/revolution. That means that the motor will run five times as fast as indexer settings. For better response and a more reliable process, 5000 steps/revolution have been set on indexer by using the MR command in all the software developed as part of the initialisation. **Plate 3** Shows a photograph of the KS-drive.

For powering up all of the four drives a single phase transformer is used. The inputs of the transformer are 240 VAC, at 50 Hz and 22.7 Amperes, and outputs are 120 VAC,

at 50 Hz and 45 Amperes. The specifications of the KS-drive are given in Appendix **B2**, and the drawing dimensions are shown in Appendix **B6**.

The KS-drive can be divided into two major parts, the digital controller board and the analog amplifier board. The controller board sends two digitized waveforms from its DAC s to the analog amplifier board. The analog amplifier board generates its own third phase command and measures the actual current to determine the correct voltage pulse width to apply to the motor's windings. A block diagram of the KS-drive is shown in **figure 53**.

The controller commands a "desired current" in the motor windings. The position of the motor shaft is sensed by the controller via the resolver attached to the motor. The positional information is used by the controller to generate a "desired current" command to the amplifier.

The generation of the current command to the amplifier by the controller is based on several parameters, not just the position of the servomotor's shaft. It is based on the desired position, which is generated by an indexer, and a previous current command to the amplifier. An indexer generates a stream of pulses which the controller collects with an up/down (i.e. clockwise/counter clockwise) counter. The resultant pulse count at any given instant of time is the desired position. The counter subtracts the motor's actual position from this desired position to

determine the positional error. This positional error is put into a recursive equation along with the previous position error and previous commands to the amplifier, to generate the current command for the amplifier **(96)**.

After every 512 microseconds the resolver is read. This provides positional information. The error value for the immediate time cycle is added to error of the last 10 time cycles to produce the total following error.

All of the position compensation (**PID** and velocity gains) are handled by the digital controller board. The recursive equation is an approximation of an analog, continuous-time PID network, which is used quite often for the puspose of stabilizing conventional servo systems.

The most important aspect of a servo system is setting the controller's "gains". Before setting new gains, other than factory default ones, it is necessary to know how each of them effects the response and nature of the application. The following outline describes how the **PID** and **V** (Proportional, Integral, Derivative and Velocity) gain affect the system response.

Proportional gain: affects the systems stiffness and accuracy. High proportional gain, will cause resolver feedback signals to be amplified, and the system will start oscillating. In this case, it should be kept below that oscillating value.

Integral gain: allows the system to compensate for positional errors in static position by slowing down the electronic response time, so that it more closely resembles the response of the mechanical components.

Derivative gain: Adds damping effects to the system. In the case where the system is oscillating which may occur at the end of a move or during a change in velocity. By increasing the derivative gain the ringing will be reduced.

Velocity gain: This is used to affect the overall responsiveness of the system. If the system is overshooting badly or there is excessive ringing that the derivative term is not able to adequately compensate, then velocity gain should be kept low or can be increased if the system is sluggish.

3.10. TUNING THE KS-DRIVE SERVO

In the KS-drive, the "gains" of the controller are the constant coefficients of the recursive equation. The form of the recursive equation determines how many of these "gains" must be adjusted in order to stabilize the system. There are two methods available to adjust a KS-drive's servo compensation Network.

(i) The push button tuning on the front panel of the KS-drive

(ii) Through the RS-232 communication port.

New adjusted gains can then be saved in an EEPROM by any of the these methods. The PID loop diagram is shown in **figure 54**.

There are five red push buttons on the front of the drive labelled **UP, DOWN, PROPORTIONAL GAIN, INTEGRAL GAIN,** and **VELOCITY GAIN.** There is also a two digit display. All the tuning functions can be performed by pressing one or more buttons down and releasing them at the same time as shown in **table 4** . While pressing any of the push button tuning combinations, the appropriate value can be seen on two digit display.

UP	DOWN	P	I	V	CONDITION
0	0	0	0	0	Display off/unless error LED is on
0	0	+	0	0	Display current PROPORTIONAL value
+	0	+	0	0	Increase PROPORTIONAL value.
0	+	+	0	0	Decreade PROPORTIONAL value.
0	0	0	+	0	Diplay current INTEGRAL value.
+	0	0	+	0	Increase INTEGRAL value.
0	+	0	+	0	Decrease INTEGRAL value.
0	0	0	0	+	Display current VELOCITY value.
+	0	0	0	+	Increase VELOCITY value.
0	+	0	0	+	Decrease VELOCITY value.
0	0	0	+	+	Display currer DIFFERENTIAL value.
+	0	0	+	+	Increase DIFFERENTIAL value.
0	+	0	+	+	Decrease DIFFERENTIAL value.
0	0	+	0	+	Display current DRIVE address.
+	0	+	0	+	Increase DRIVE address(max. of 15)
0	+	+	0	+	Decrease DRIVE address(min. of 1)
0	0	+	+	0	Return to factory default values.
0	0	+	+	+	Save current tuned values.
+	+	0	0	0	Reset the Drive.

Note: + = Push, 0 = Not Push, All other combitions will be ignored.

Table 4. Combination of push buttons shows the tuning procedure through push buttons.

For developing communications between all four drives
and the micro-computer through RS-232 interface, the drives
need to be assigned a seperate device address. This has
been done by pressing P and V buttons followed by up/down
buttons on the front panel of the drives. Each drive is
then labeled by a number, 1 to 4. Drives numbered 1 to 4
are connected to the servomotors, for linear motions along
the X and Y axes, and for rotary motions around Y and X
axis respectively. By pressing **P**, **I**, and **V** term buttons
and releasing them at the same time, the new values can be
saved in non volatile **EEPROM**.

The PID and V gain values represent a percentage of
the maximum value that the term (PID and V) is allowed to
achieve by push button or the RS-232 interface. The form
of the equation for the tuning setup by both methods is

Gain Value = Term Maximum x Term Percentage (1 to 99%)

The term maximum can only be changed through the
RS-232 interface, which is motor dependent.

3.11. RS-232 INTERFACE OF THE KS-DRIVE

The RS-232 interface not only allows PID V gains, and
maximum terms to be set, but it also has a wide range of
servo commands which can be accessed by the software. There
are approximately 45 servo commands. A summary of these
commands is given in Appendix **B9** . Communicating with all

four drives by a micro-computer based software through the RS-232 port involves a daisy chain cycle. The KS-drive communication format is tuned at 9600 baud rate, 8 data bit 1 stop bit and no parity on RS-232 25-D pin connector pin 2 (receive data), pin 3 (transmit data) and pin 7 (ground) are the ones used. This software uses serial communications port **COM1** to establish the communications. When any of the drives is enabled by "E" command, to communicate by servo commands, the front panel push button tuning will be disabled, except if the "F" command is issued or to turn off and on the power in drive units. All the servo commands need to be prefixed with device address during communicating

By using these servo commands different parameters like motor resolution, peak current, average current, instant peak and average currents, **PID** and **V** gain values, maximum PID and V terms, resolver position, etc. can be displayed on the computer screen and changed as well. A sample program has been developed as shown in Appendix **B10**, this program gives access to display different parameters, test the status (by sensing stiffness of the motor shaft) change the PID and V values. If the desired performance of the system is satisfactory, these parameter values can be saved in the non volatile EEPROM of the drive. This appendix shows the present settings of all the four drives as well. If any fault occurs in the KS-drive during operation, then this fault will be indicated on the drive's visual LEDs, and numerical error code will be

displayed on the two digit display on the front panel of the drive. This fault can also be be detected by using "RSE" command.

3.12. VISUAL INDICATORS OF THE KS-DRIVE

There are five **LED** indicators on the front panel of the drive. Each of them is marked as **DRIVE TEMP., MOTOR TEMP., REGEN, POWER** and **FAULT**.

(i) DRIVE TEMP : This **LED** is normally off. When it lights, indicating over temperature in the drive. This error causes the FAULT LED to light as well. This over temperature fault can be avoided by downing the power or using a fan kit.

(II) MOTOR TEMP.: This **LED** is normally off When lit, it will be red, indicating an **over temperature** condition in motor. It is derived by the microprocessor based on the average current being sent to the motor. In this case motor may not be working to the top of its speed/torque curve. Then this may necessary to reduce Peak current setting by using **CCP** servo command through RS-232 interface.

(III) REGENeration LED: It will be on (normally off) when the motor is generating power that is being dissipated in the power dump resistor if it is on more than 5% of the time or 10 seconds, then some factors like motor size,

duty cycle calculations, adding external resistors to dissipate power generated by load or changing gear ratio, must be reconsidered.

(iv) POWER: This bi-colour LED is green under normal operating conditions. If this LED is red, it indicates a microprocessor failure. If this microprocessor failure fault is temporary, then by switching off and on power to the drive clears this condition.

(V) FAULT: Normally this LED is off. It will be red if there is a microprocessor detectable error condition. When the drive faults the error light will come on and the numerical display will show a numerical error code, or the RSE command can be issued to determine what condition exists. The error code and expected condition are given in table 4.

CODE	CONDITION
11	over temperature.
19	short on motor circuit.
20	following error exceeded.
21	outside allowable deadband.
22	max. average current exceeded.
30	EEPROM checksum error.
40	Both limits engaged and indexer commands attempting move.
60	RS-232 command shutdown.
61	Incoming indexer pulses .

Table 5.   Shows KS-drive error codes and their meaning.

3.13. AC BRUSHLESS SERVO MOTORS

There are four AC brushless servo motors which have been utilized in this prototype rig to generate 3-dimensional complex shapes. Three of them are KS-220, and one of the lower size KS-210. Two of the three KS-220 motors are utilized for linear motion along X and Y-axes. One of the KS-220 motor is used for rotary motion around Y-axis (beta), which is attached to a gear box (Drivematic SA 1002) having gear ratio of 18:1. An other motor KS-210 is used for rotary motion around X-axis (alpha), which is attached to a gear box (Harmonic Drive HDGH 14) having gear ratio of 100:1. The specifications of these motors are shown in Appendix B3, and drawings are shown in Appendix B7. An AC servomotor runs when the rotor magnetic field tries to follow the stator turning magnetic field created by the three-phase AC current. By changing three phase current frequency motor achieves different velocities. STEP pulses applied first slowly, and then more quickly have the effect of accelerating the motor. Figure 55 shows the torque-speed curve of KS-210 and Figure 56 of KS-220 motor as supplied by the manufacturer (97). The power amplifier section of the drive utilizes a MOSFET 20 KHz PWM current, which improves low speed smoothness (95).

Present setting values of average current, peak current and other parameters of all the motors are shown in Appendix B10. The values of the average and peak currents set for three KS-220 motors are kept at maximum.

These average current and peak current values for motor KS-210 are brought down to meet the torque input requirements for the gear box (Harmonic Drive HDGH 14) attached to the motor for pitch motion. According to gear box supplier literature, this gear box (HDGH 14, 100:1) can generate nominal and peak torque values of 8 Nm and 20 Nm respectively. This gear box has an efficiency of 70% Therefore the nominal and peak input torque values required for this gear box will be

$$T_{(motor)} = T_{(gear\ box)} / (ratio\ x\ \eta)$$

Nominal torque required $\quad T_m = 8 / (100 \times .7)$
$$\approx 0.1143\ Nm$$

Peak torque required $\quad T_m = 20 / (100 \times .7)$
$$\approx 0.2857\ Nm$$

The literature supplied by Compumotor shows the linear relationship between torque and current given to motor as shown in figure 58.

$$Y = mx + c \underline{\hspace{6cm}} \quad \textbf{(i)}$$

If $\quad x = 1 \quad$ Amperes $\quad => \quad Y = 0.1913 \quad$ Nm / Amp. (ii)

$\quad x = 4.1 \quad$ Amperes $\quad => \quad Y = 0.13997$ Nm / Amp. (iii)

By solving (ii) and (iii) we get

$m = - 0.01656 \quad$ and

$c = 0.20786$

By putting these values of m and c in (i)

$T / A = -0.01656\ A + 0.20786$

Where T = Torque in Nm, and A = Current in amperes

$T = - 0.01656\ A^2 + 0.20786\ A \underline{\hspace{1.5cm}} \textbf{(iv)}$

By solving equation number (iv), we get the torque (T) values of 0.1143 and 0.2853 Nm, at current (A) values of 0.576 and 1.569 amperes respectively. Whereas, the original average and peak current values for this motor (KS-210) were set at 1.5 and 8.00 amperes generating the nominal and peak torques of 0.23 Nm and 0.7 Nm respectively.

3.14. PROBLEMS ENCOUNTERED IN INTERFACING

The interfacing used in this CNC system is available commercially from Parker Compumotor company. The catalogs (95,96,97) and information supplied by their local agent is not fully up to date and complete.

One of the major problems encountered was that a lot of information about PC23 indexer command was incorrectly detailed and in many instances the information was contradictory, confusing and disorganised. In the first sight these commands seem to be straight forward. However, in attempting to implementing these it was found that the resulting movements were different from what it should be. In order to avoid damage to the mechanical parts of the manipulator substantial effort had to be devoted to rectify the situation. For example, if acceleration and velocity were needed to be less than one rev. / sec^2 and rev. / sec , and that value was calculated by the computer in 1st and 2nd precision form (exponential form) then the PC23 indexer took that value as a whole number ignoring the

instruction format for fractional number. By experiment, it was also found that the values of acceleration and velocity less than the minimum specified could be used. A number of command are also missing from the 'main section of commands' and a few commands are not properly described, that is how to implement them. In most cases it was possible to distinguish between motor command and encoder commands, but frequently it was difficult.

Synchronization of the PC23 indexers is another problem, which is still unsolved. For synchronization three motor axes on one indexer is done by using global command "G123", which initiates all three motor axes motion approximately within 150 μ seconds of one another (100). As in present research work, we are using two PC23 indexers. This time delay of initiating all the motor axes on both indexers will cause some inaccuracy in the profile to be generated.

In the case of KS-drives, the PID and V values including their term maximum limits are motor dependent (101). The maximum limits which can be set for the KS-210 and KS-220 motor sizes are not given in the KS-drive manual. It could have been more helpful for better system performance if these values were given. Beside these problems mentioned above a few commands like "F" (disable indexer communication) and KS-drive command "HELP" are not working.
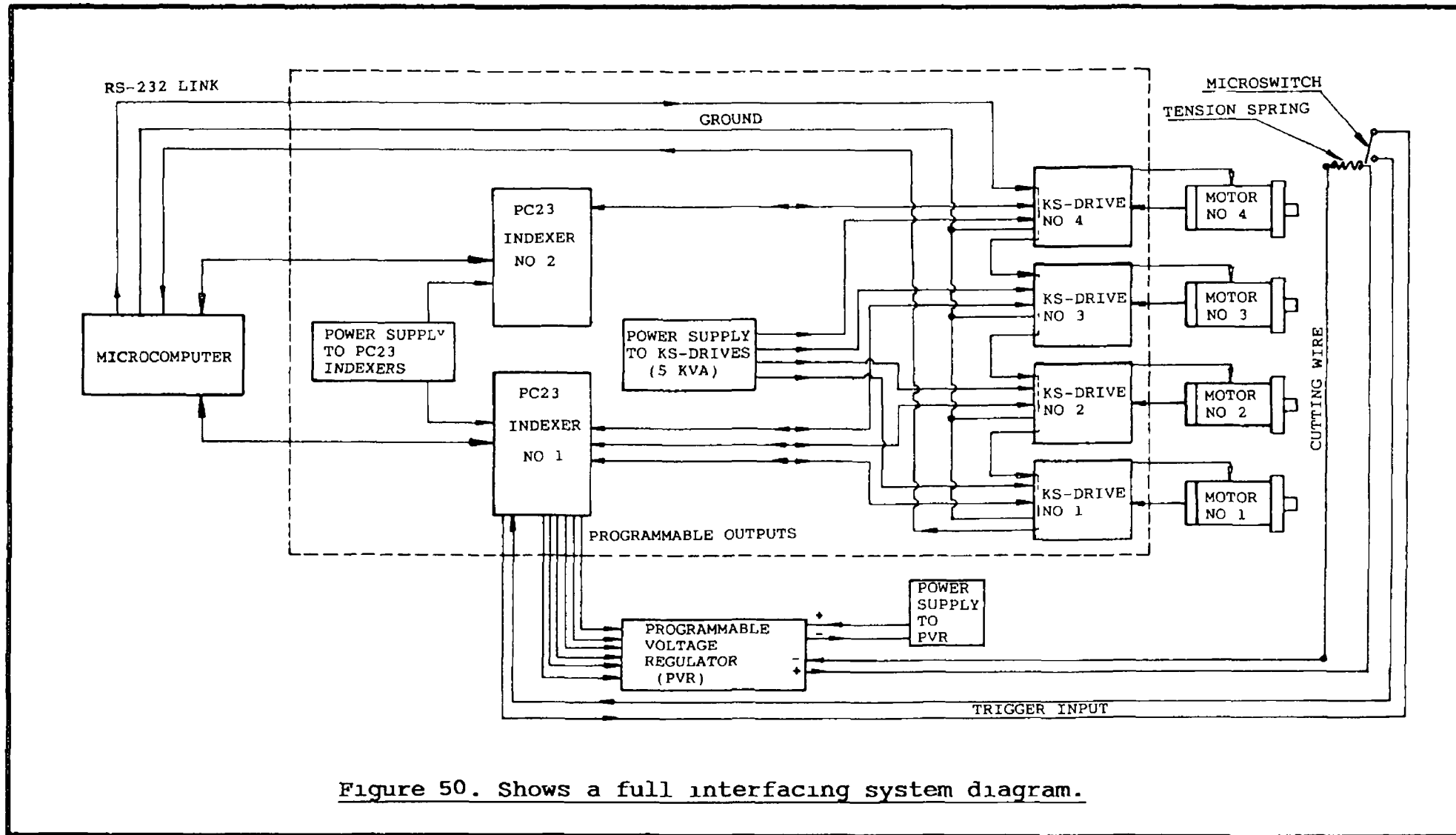
Figure 50. Shows a full interfacing system diagram.

TRIGGER INPUTS FROM EXTERNAL
SENSORS / SIGNAL SOURSES

WRITE ONLY REGISTER

INDEXER COMMANDS FROM COMPUTER

PROGRAMMABLE OUTPUTS

CW AND CCW LIMITS

HOME ENABLE LIMITS

STEPS

DIRECTION

POWER SHUTDOWN

INDEXER RESPONSES TO
MICROCOMPUTER
READ ONLY REGISTER (IN)

WRITE ONLY REGISTER (OUT)

READ ONLY REGISTER (IN)

OPTICALL ISOLATED

IDB

ODB

CB

SB

BASE ADDRESS
INDEXER CONTROL COMMANDS
AND RESPONSES

BASE ADDRESS+1
(HAND SHAKING)

INTERFACE

MICROPROCESSOR

POWER
SUPPLY

OPTICAL
ENCODER
INTERFACE

PULSE
CIRCUIT
AXIX-1

PULSE
CIRCUIT
AXIS-2

PULSE
CIRCUIT
AXIS-3

PULSES TO
DRIVE 1

PULSES TO
DRIVE 2

PULSES TO
DRIVE 3

FEEDBACK SIGNALS FROM ENCODER

Figure 51. An indexer system diagram.

POWER SUPPLY (0 TO 30 DC VOLTS)

VOLTAGE REGULATOR LM-338

C1

A

R = 120 ohm

B

C2

(✳)

Ts

Ms

Cw

P1 P2 P3 P4

T1 T2 T3 T4 T5

PROGRAMMABLE OUTPUTS FROM INDEXER - MICROCOMPUTER

MICRO-COMPUTER

PC23 INDEXER

TRIGGER INPUT
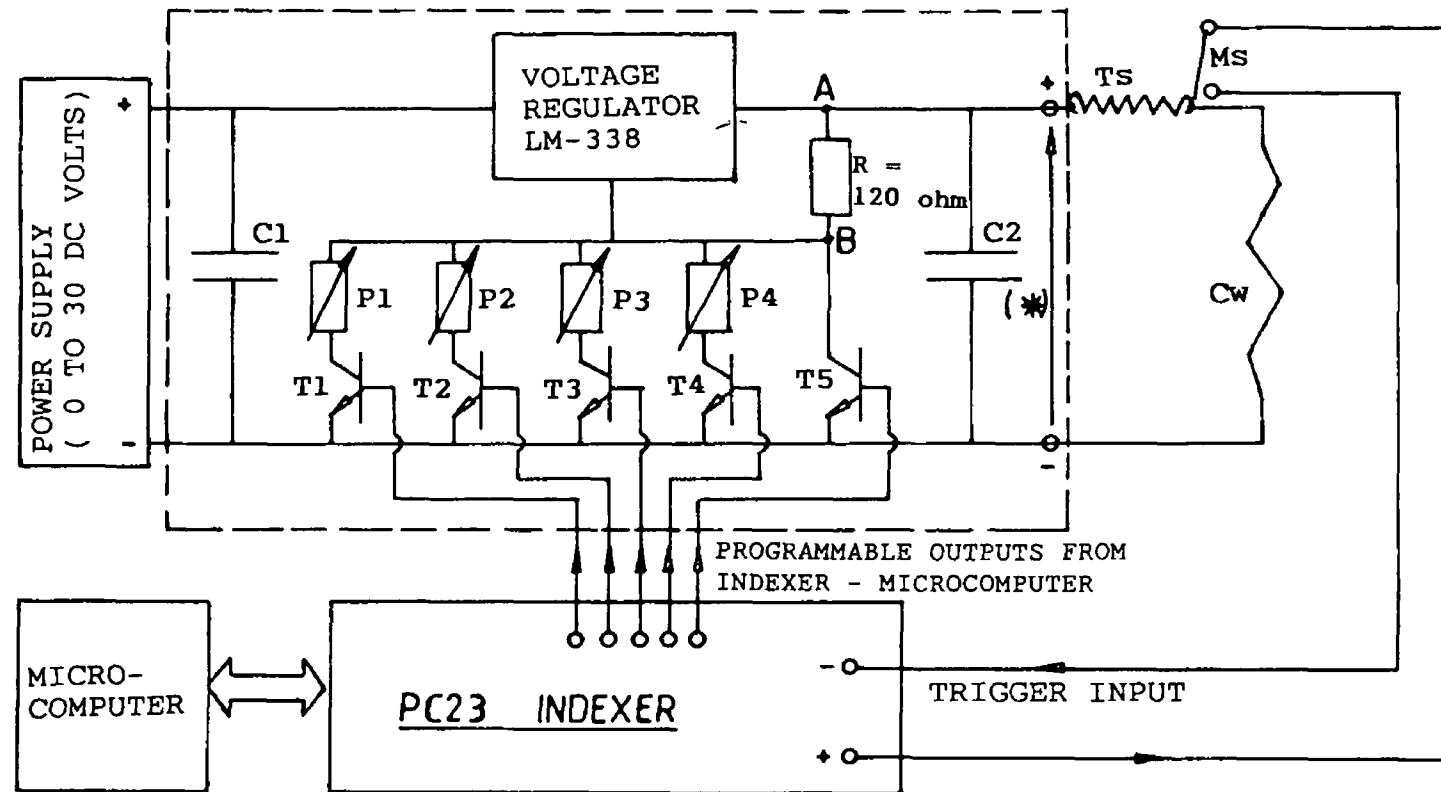
(✳) = TOTAL PROGRAMMABLE OUTPUT VOLTAGE (1 25 TO 30 VOLTS)
C1 = 1 µF   C2 = 0 1 µF   Ms= MICROSWITCH
Cw = CUTTING WIRE   Ts = TENSION SPRING Pi= POTENTIOMETERS
Ti = 2N222 2A (NPN) 50 K Ohm   10%

Figure 52. Shows a circuit diagram of the Programmable Voltage Regulator (PVR) circuit.
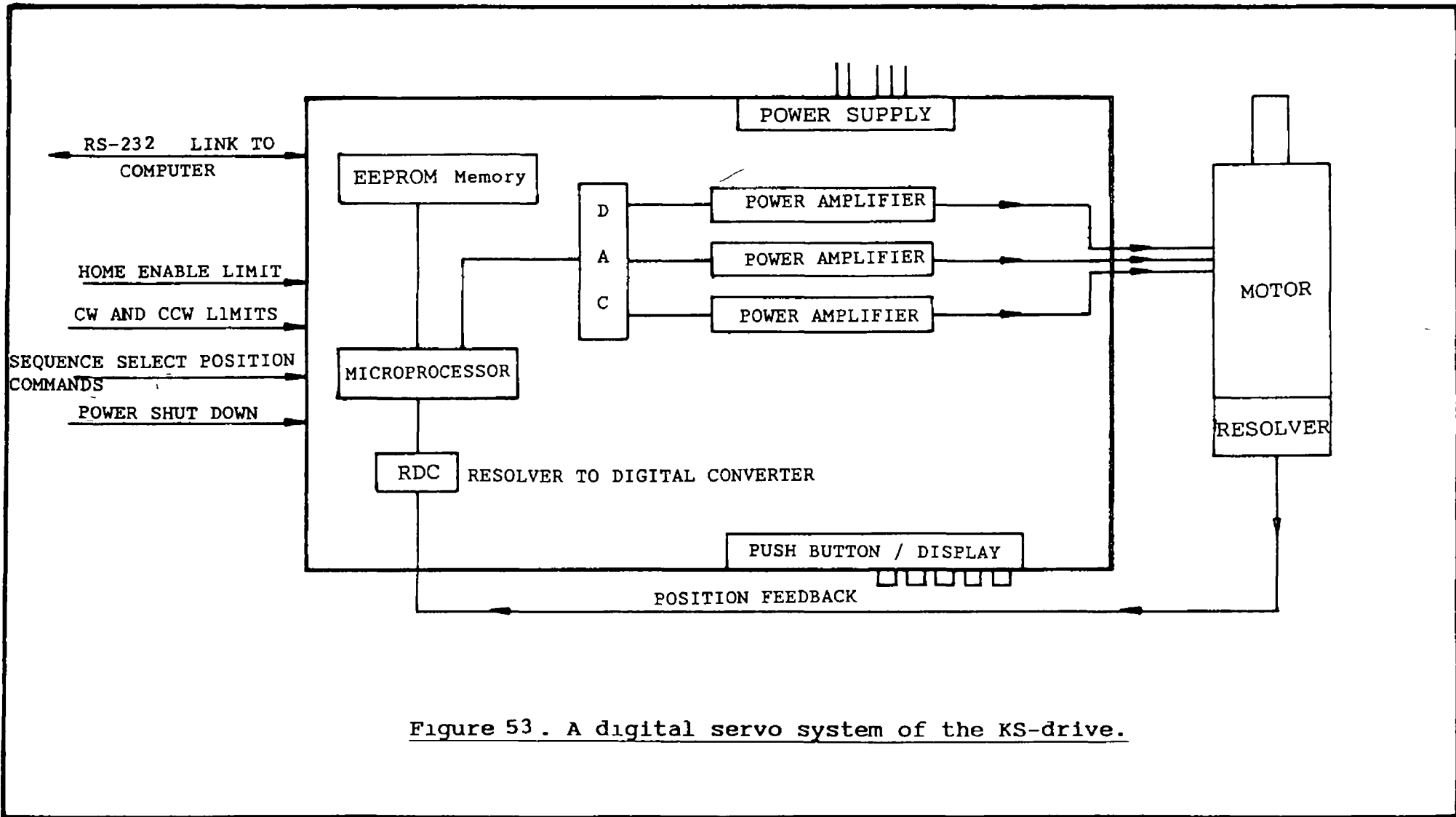
Figure 53. A digital servo system of the KS-drive.

COMMANDED POSITION → Ep → POSITION LOOP PID EQUATION → Mp → Ev → VELOCITY LOOP → Mv → POWER STAGE → VOLTAGE AND CURRENT TO MOTOR → MOTOR / RESOLVER

MEASURED VEOCITY

MEASURED POSITION

RESOLVER TO DIGITAL CONVERTER

T = 512 μ Seconds
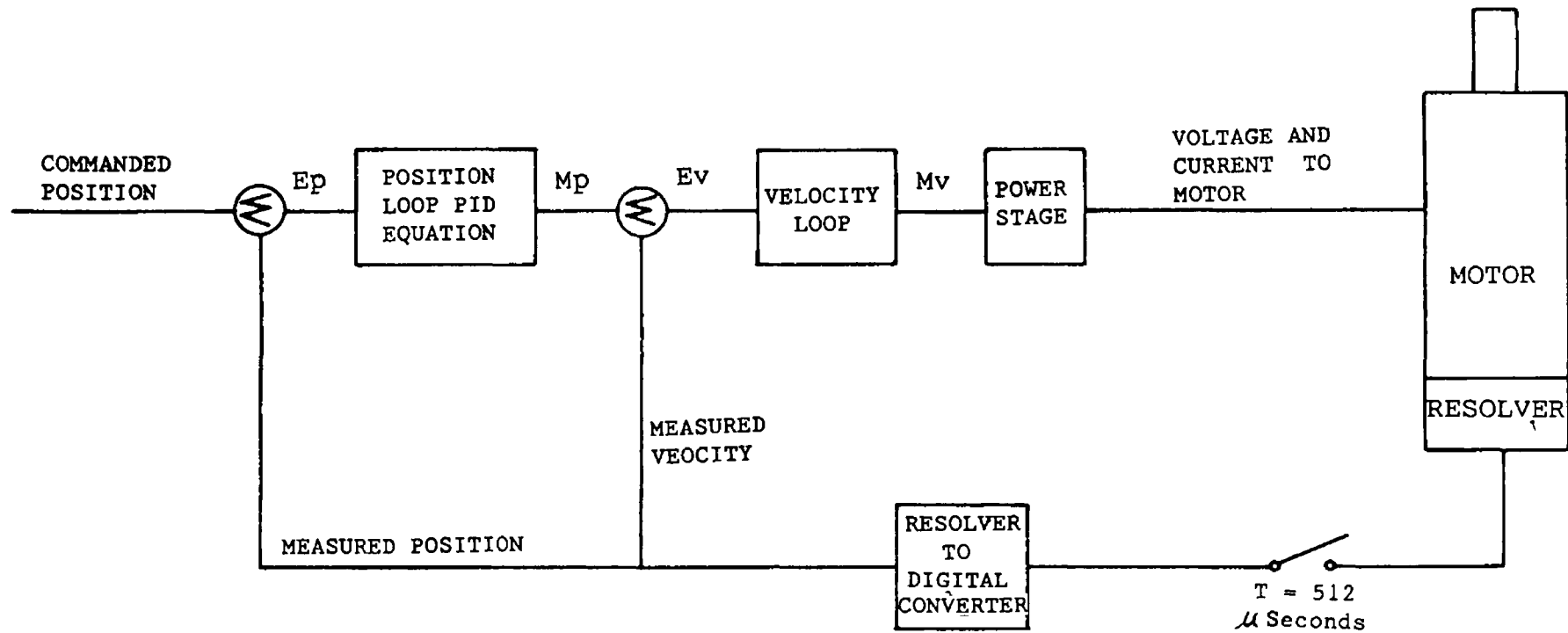
Ep = SYSTEM POSITION ERROR   Mp = SYSTEM POSITION CORRECTION FACTOR
                                              (COMMANDED VELOCITY)
Ev = SYSTEM VELOCITY ERROR   Mv = SYSTEM VELOCITY CORRECTION FACTOR

Figure 54 . PID loop block diagram of the KS-DRIVE.
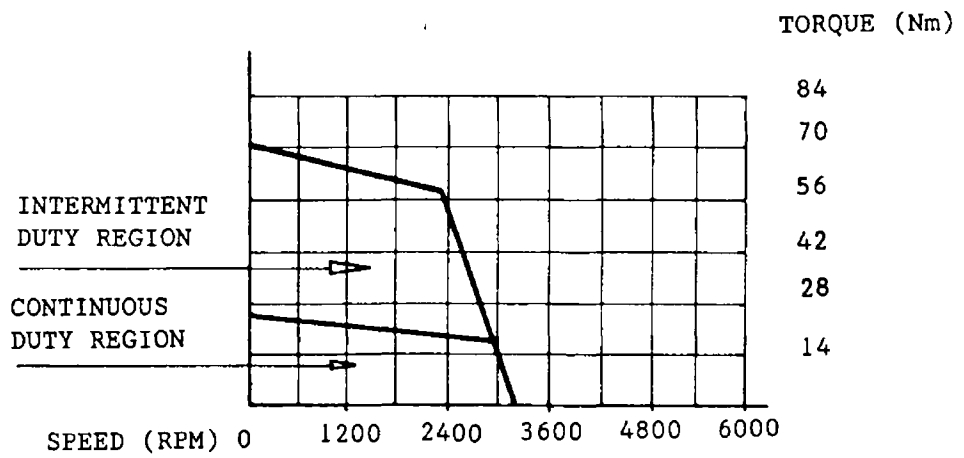
Figure 55. Shows torque-speed curve of KS-210 motor.
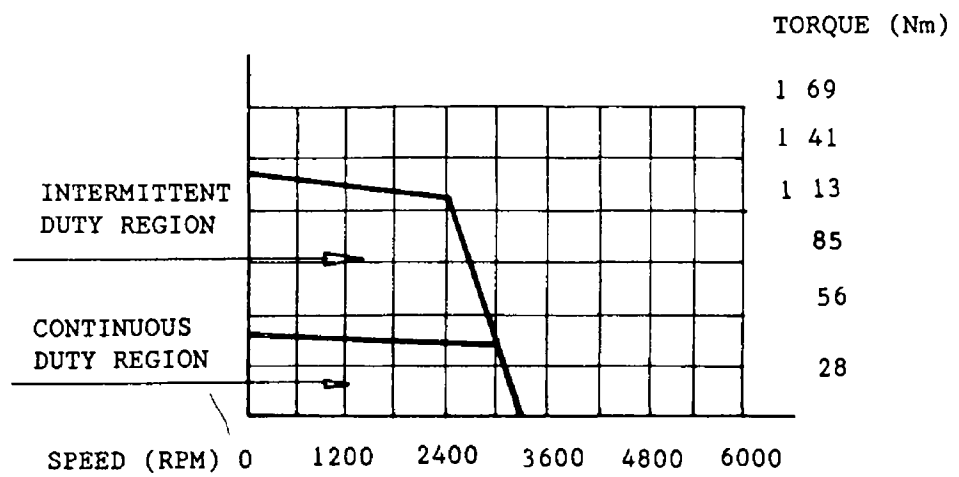
Figure 56. Shows torque-speed curve of KS-220 motor.
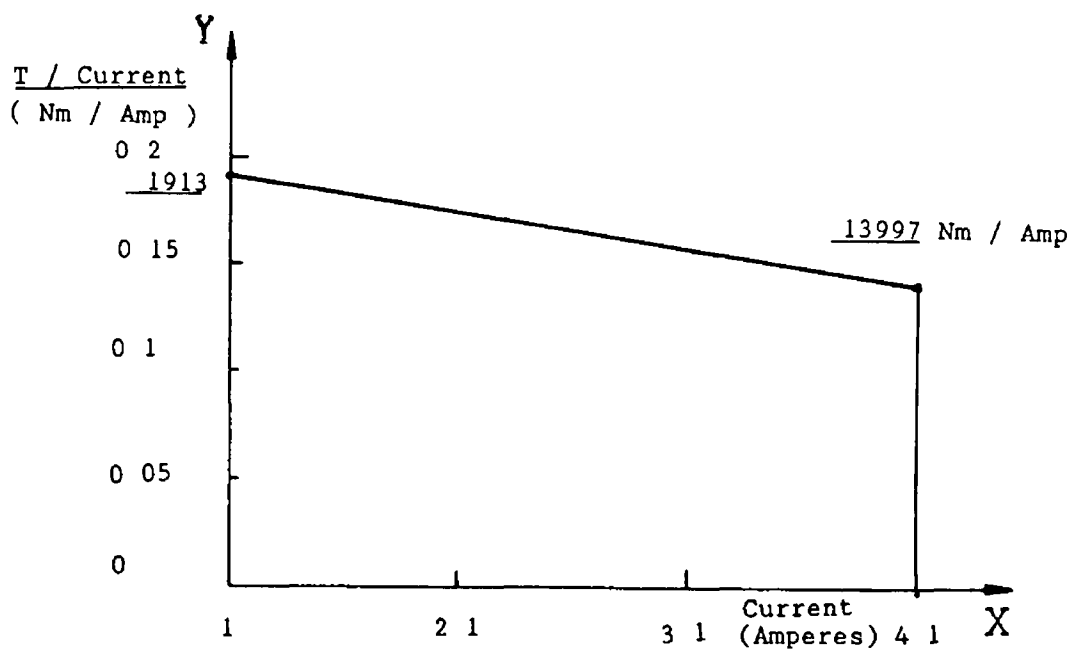
Figure 57. Shows relationship between torque and current.

PLATE 3. THE KS-DRIVE

CHAPTER FOUR

PATH PLANNING AND MOTION CONTROL FOR SHAPE GENERATION

/

4.1. INTRODUCTION

Motion control of the precise robotic manipulator for the manufacture of 2-D/3-D complex shaped geometries needs to be programmed in a careful and appropriate way.

For an accurate 3-D shape generation, each motor needs to be controlled in a synchronized fashion. The geometry describing the top and bottom surfaces to be manufactured for any particular shape needs to be precise and in a well planned way. The geometries for different 3-D shapes described in this chapter were developed in one of the following three different ways. Firstly, some of the shapes were described in terms of mathematical and geometric functions. Secondly, some other shapes were described by means of built-in geometrical data kept within the program. Finally by inputting the X and Y co-ordinates through the key board by the user to describe the shapes other than those described using the first two ways

By careful planning of motion control and geometry description the problems like, overcut, undercut or intermediate sections overlapping the bottom surface are avoided. Each software developed for different 2-D/3-D

shapes is PC based and describes the shape geometry as well as controls all the path planning and motion control parameters.

Each of the 3-D shape generating software is sub-divided into two parts. The first part describes the calculations for top, bottom and intermediate section geometry. This part also draws the profiles of these sections on the screen and shows the wire cutting path between the top and bottom surfaces. The first part of the programs for all different 3-Dimensional geometries are then linked to the second part of the program. The second part of the program then plans path, sets machining conditions and controls motion for die generation for all 3-D first part programs.

2-D software for spur gear manufacturing is also sub-divided into two parts in the same manner as for 3-D die cavity generation.

For better response and performance of the system three other functional software were also developed other than those for describing the 2-D \ 3-D geometries. One of the special purpose software is for changing the servo-parameters in the KS-drive to optimise the system response and for matching the parameters of KS-drive with PC-23 indexer, e.g; motor resolution. The other functional software allows the user to configure and

regulate the voltage value in the cutting wire through the PVR. The third software can be used to manoeuvre the manipulator through arrow keys along X and Y-axes.

4.2. DIE GENERATION PRINCIPLE

The geometry describing the top and bottom surfaces for 3-D shapes by PC based software is done by knowing the X and Y co-ordinates on both the surfaces for different profiles. The principle of generating 3-D die cavity of good quality lies in the way the geometry is described for both surfaces at a known distance (Z-coordinate) from each other.

From the points representing the top and bottom surfaces the 3-D die profile can be generated. The number of points representing the surfaces must be the same and both the surfaces must also be flat and parallel. The program calculates the angles alpha and beta for the corresponding points between the top and bottom surfaces around X and Y axes respectively. By connecting these points between the top and bottom surfaces according to the angles alpha and beta splines are formed in space, as represented in chapter two **figure 26.**

Once the path profiles based on these points and angles are known for the manipulator to follow, then the computer program goes through a number of sub-routines to

set machining conditions such as setting PC-23 indexer operating mode, motor resolution, user selected workpiece feedrate and voltage for the cutting wire.

After getting all the above information the desired 3-D die cavities were generated by two concurrent steps. Firstly, the generation of the bottom shape which was obtained by manipulating the workpiece in X and Y directions. Secondly the top surface which was obtained by rotating the workpiece around the X and Y axes to align the cutting wire with the corresponding splines between the top and bottom surfaces according to the angles alpha and beta. The process is then repeated to cover all the splines for generating the complete 3-D shape in the model material.

4.3. GEOMETRIC DESCRIPTION OF THE CIRCLE TO COMPLEX SHAPE

The geometry describing a circle at the top and noncircular complex shape at the bottom surface needs to be planned in a very careful way. The location of the points on the top and bottom surfaces for any shape needs to be accurately on the regular profile path. This is very important for the good surface generation. The better accuracy for the complex shape geometry needs to be described in a particular way. The location of X and Y co-ordinates calculated by the software for complex and circle shape, at different angles from reference zero degree in cartesion co-ordinate system, are of basic importance for good quality of the intermediate sections.

The co-ordinates describing circle shape geometry at the top surface, must be planned in such a way, sothat when they make splines with the bottom surface corresponding co-ordinates, the intermediate section of the splines should not cross the bottom surface profile. If the above condition is not true, then the intermediate sections of the die profile will be narrower then the bottom surface. This will cause the wire to be drawn through the die cavity giving imperfect bottom shape. This condition is avoided by splitting the circle shape into five arcs to form a circle shape. Each arc length is then sub-divided into a number of more smaller segments by using trigonometric functions. The complex shape is the formation of twenty arcs, and each arc is again sub-divided into smaller segments. The more matching the angles of points have with reference zero in cartesion co-ordinate system for corresponding top and bottom surfaces, the better the quality of the wire drawing flow can be achieved using the die made in this way.

The software developed to describe circle shape at the top surface, complex shape at the bottom surface and the calculations for the intermediate surface is given in the volume II Appendix **C1**.

4.3.1. GEOMETRIC DESCRIPTION FOR CIRCLE SHAPE

The geometry to describe the circle is based on simple trigonometric functions The main technique used

in here is to decide the location of each point describing the circle shape in relation to the points describing the complex shape at the bottom surface. The circle is divided into five arcs and then each arc is sub-divided into further small sectors to match the sectors at the bottom surface. The sub-routine describing the circle shape is given at the end of this topic.

In this sub-routine the data shown in line number 1160 are five sets of two numbers. The first number in each set assigned to a variable **DSY** is the angle in degrees which denotes the initial point of each arc of the circle. The sum of all the second numbers in the five sets is equal to twenty, which is equal to the number of curves on the bottom surface. Therefore, the total number of points on the complex shape (on twenty arcs) is equal to the number of points on the circle shape (on five arcs). The number of points should be divisible by 20 , because of twenty number of arcs on the complex shape. The more the number of points the finer the die profile will be. The total number of points for the die generation should be 40, 60, 80 or 100. The calculations of points on each arc of the circle are done in a loop starting at line number 1230. The X and Y co-ordinates are calculated by well known trigonometric functions;

$$XT = RO * COS(SY) \qquad \text{(REFER STATEMENT 1250)}$$

$$YT = RO * SIN(SY) \qquad \text{(REFER STATEMENT 1260)}$$

Where **RO** is the radius of the circle and **SY** is the incremental angle in radians with reference to zero.

The distance (**RT**) between the centre of the circle and each point on the circle boundary is calculated by using the following equation

$$RT = \sqrt{XT^2 + YT^2} \qquad \text{(REFER STATEMENT 1290)}$$

The angle which the line connecting the centre with each point makes with reference to zero line is calculated by using the following equation

$$TTHETA = \tan^{-1}(YT/XT) \qquad \text{(REFER STATEMENT 1330)}$$

The TSTHETA is the angle of each sector in radians of the corresponding points (REFER STATEMENT 1380). Then the sector area is found by using equation;

$$TSAREA = (RT^2 * TSTHETA) / 2 \qquad \text{(REFER STATEMENT 1420)}$$

Then the total area is also found in the same way except using the angle upto the point the area is being calculated (REFER STATEMENT 1410).

After calculating all these data for each point, the computer program prints these data on the screen including total area enclosed by the circle profile. A

typical printout of these data for 80 points is shown in **table** 7.   The point number 81 is calculated to enclose the circle, which is the same as point number one and is the result of line number 1220.

```
1130 REM ------------------------------------------------
1140 '  TOP SURFACE (CIRCLE) CALCULATION STARTS FROM HERE
1150 REM ------------------------------------------------
1160 DATA 120,4,   140,5,   260,4,   280,3,   360,4
1170 FOR I = 1 TO 5
1180 READ DSY(I),CR
1190 DSY(I) = DSY(I)*DR
1200 DSY=(DSY(I)-DSY(I-1))/(NP*CR)
1210 SY = DSY(I-1) - DSY
1220 IF I = 5 THEN NOP = (NP*CR)+1 ELSE NOP = (NP*CR)
1230 FOR J = 1 TO NOP
1240 SY = SY + DSY : M = B+J
1250 XT1(I,J) = (RO * COS(SY))
1260 YT1(I,J) = (RO * SIN(SY))
1270 XT(M) = XT1(I,J)
1280 YT(M) = YT1(I,J)
1290 RT(M) = SQR( XT(M)^2 + YT(M)^2 )
1300 IF M = N+1 THEN GOTO 1370
1310 IF XT(M) < 0 THEN 1350
1320 IF YT(M) < 0 THEN 1370
1330 TTHETA(M) = ATN( YT(M) / XT(M) )
1340 GOTO 1380
1350 TTHETA(M) = PI + ATN( YT(M)/XT(M) )
1360 GOTO 1380
1370 TTHETA(M) = (2*PI) + ATN( YT(M)/XT(M) )
1380 TSTHETA(M) = TTHETA(M) - TTHETA(M-1)
1390 IF M = 1 THEN RT(0) = RT(1)
1400 RT(M) = ( RT(M) + RT(M-1) ) / 2
1410 TAREA(M) = ( RT(M)^2*TTHETA(M) ) / 2
1420 TSAREA(M) = (RT(M)^2 * TSTHETA(M) ) / 2
1430 P = XT(M) : GOSUB 3480 : XT = VAL(P$)
1440 P = YT(M) : GOSUB 3480 : YT = VAL(P$)
1450 P = RT(M) : GOSUB 3480 : RT = VAL(P$)
1460 P = TTHETA(M)*RD:GOSUB 3480:TTHETA  = VAL(P$)
1470 P = TSAREA(M) : GOSUB 3480 : TSAREA = VAL(P$)
1480 P = TAREA(M)  : GOSUB 3480 : TAREA  = VAL(P$)
1490 PRINT "|"M;TAB(9);XT;TAB(20);YT;TAB(30);RT;
TAB(40);TTHETA;TAB;(52);TSAREA;TAB(63);TAREA;TAB(74)"|"
1500 IF J = NOP   THEN GOTO 1520
1510 NEXT J
1520 B = (B+J)
1530 IF I = 5 THEN GOTO 1550
1540 NEXT I
1550 PRINT":_____
1560 PRINT
1570 PRINT "TOTAL AREA OF THE TOP SURFACE (CIRCLE AT Z
TAREA(M);"=";ZT"mm) =";  mm Square."
```

4.3.2. GEOMETRIC DESCRIPTION FOR COMPLEX SHAPE

The complex shape is described by splitting the shape geometry into twenty arcs having different centres in the cartesian co-ordinate system as shown in **figure 59a.** Three sub-routines describing the complex shape are given at the end of this topic. The data given in line numbers 1720 to 1860 Appendix **C1** are the X and Y co-ordinates for three points on each arc; the first point (X_f, Y_f), the middle point (X_m, Y_m) and the final point (X_s, Y_s).

The sub-routine reads this data and multiplies with the user selected magnification factor to bring the co-ordinates on required scale (REFER STATEMENTS 1890 - 1910). If the co-ordinates for three points on the arc are known, then the equation for finding out the centre co-ordinates can be derived in the following way by referring to **figure 59b.**

$$(X_f-X_c)^2 + (Y_f-Y_c)^2 = R^2 \underline{\hspace{3cm}} 1$$

$$(X_m-X_c)^2 + (Y_m-Y_c)^2 = R^2 \underline{\hspace{3cm}} 2$$

$$(X_s-X_c)^2 + (Y_s-Y_c)^2 = R^2 \underline{\hspace{3cm}} 3$$

By subtracting 2 from 1, we obtain

$$X_f^2 - X_m^2 + Y_f^2 - Y_m^2 - 2X_c(X_f - X_m) - 2Y_c(Y_f - Y_m) = 0 \underline{\hspace{1.5cm}} A$$

Now by subtracting 3 from 1 , we obtain

$$X_f^2 - X_s^2 + Y_f^2 - Y_s^2 - 2X_c(X_f - X_s) - 2Y_c(Y_f - Y_s) = 0 \underline{\hspace{1cm}} B$$

Subtracting **B** from **A** , and simplifying we get

$$X_C = \frac{X_s{}^2 - X_m{}^2 + Y_s{}^2 - Y_m{}^2 + 2Y_C(Y_m - Y_s)}{2(X_s - X_m)} \qquad\qquad \text{C}$$

Now by substituting the value of X_C from **C** into **A**, we get

$$Y_C = \frac{(X_m - X_s)(X_f{}^2 - X_m{}^2 + Y_f{}^2 - Y_m{}^2) + (X_f - X_m)(X_s{}^2 - X_m{}^2 + Y_s{}^2 - Y_{m^2})}{2(Y_f - Y_m)(X_m + X_s)(X_f - X_m)(Y_m - Y_s)}$$

By substituting this value of Y_C into **C**, we get the value of X_C (REFER STATEMENTS 1920-1950)

Once the centres of the arcs are known, then by referring to **figure 59c** the angles of the arcs will be according to following equation (REFER STATEMENTS 1960 - 2000)

$$\textbf{ANGLE} = \tan^{-1}\left[\frac{A1*B2 - A2*B1}{A1*A2 + B1*B2} \right]$$

$$\text{where} \quad \textbf{A1} = \frac{Y_C - Y_f}{X_C - X_f} \quad , \quad \textbf{A2} = \frac{Y_C - Y_s}{X_C - X_s}$$

and $\quad$ **B1 = B2 = -1**

After calculating the angles of the arcs making a complex shape, we need to know the **ANGLE1**, which is being formed by the first point of the arc with reference to the centre of the arc. The **ANGLE1** is being calculated by the following equation (REFER STATEMENT 2030).

$$\textbf{ANGLE1} = \tan^{-1}[\ (Yf-Yc)\ /\ (Xf-Xc)\ ]$$

The radius of each arc, between the first point and the centre of the each arc is calculated by the following equation, by referring to **figure 59b**,

$$R(I) = \sqrt{(X_f - X_c)^2 + (Y_f - Y_c)^2} \quad \text{(REFER STATEMENT 2110)}$$

Once we have calculated the co-ordinates of the centre co-ordinates and radius of each arc, **ANGLE** and **ANGLE1** values for all twenty arcs, we need to determine the co-ordinates of additional points on each arc to define the complex shape more effectively. These calculations are carried out in nested loops between line numbers 2140 - 2260. Each **ANGLE** of an arc is sub-divided into **NP** (REFER STATEMENT 1000, APPENDIX C1, **NP =(N/20)**, Where, **N** = the total number of points on the complex profile). The co-ordinates of the first point of each curve are started from **ANGLE1**, and rest of **NP** co-ordinates are calculated by adding the incremental angle value equal to **(ANGLE/NP)** to the following equations;

$$XB1 = (R * COS(SY)) + XC \quad \text{(REFER STATEMENT 2190)}$$

$$YB1 = (R * SIN(SY)) + YC \quad \text{(REFER STATEMENT 2200)}$$

where **R** is the radius, and **XC** and **YC** are the centre co-ordinates of each arc.

The area calculations are carried out at another

loop starting at line number 2350. The resultant distance between the centre of the shape and every calculated point on the boundary of the shape, as shown in **figure 60a** is calculated by the equation

$$RB = \sqrt{XB^2 + YB^2} \qquad \text{(REFER STATEMENT 2360)}$$

The angles generated by each point on the boundary with reference to zero is calculated by the following equation ;

$$BTHETA = \tan^{-1} (YB/XB) \qquad \text{(REFER STATEMENT 2410)}$$

Where BSTHETA is the angle in radians between two consecutive points on the shape profile. Therefore the sector area can be calculated by using equation;

$$BSAREA = (RB1^2 * BSTHETA) / 2 \qquad \text{(REFER STATEMENT 2490)}$$

For close approximation of the area calculations of the complex shape, **RB1** variable is used , which is the mean of both sides of the arcs (REFER STATEMENT 2480)

The total area is then found by adding all the sector areas. The printout of the data calculated for this shape is given in **table 8.** From table 8, sector areas of segment numbers 16-20, 32,33 and 57-61 can be seen as negative. These area values are then subtracted from the total areas. The negative sign is originally the function of the angle (**BSTHETA**), which is used in

area calculations for each sector. If at any stage, the angle (**BSTHETA**) is smaller than the angle used in earlier stage for sector area calculation, then the new sector area being calculated as additional area, which is shown in table 8 by negative sign. This area has already been counted as a part of the total area as shown in **figure 60b**. The photograph of the die generated using this data is shown in **PLATE 4** Total machining area for plate 4 was calculated 7523 725 mm², which was machined in a practical time of approximately 17 minutes and 19.12 seconds at a workpiece feedrate of 800 mm²/min for the workpiece thickness of 39 mm.

At the end, the program calculates the total area enclosed by this complex shape profile and the reduction ratio of the area at this section. This can also be seen at the bottom of table 8.

```
1580 PRINT "**********************************************"
1590 PRINT " CALCULATIONS  FOR  BOTTOM SURFACE (COMPLEX) "
1600 PRINT "**********************************************"
1610 GOSUB 3630 : CLS : SCREEN 1
1620 ERASE XT1, YT1, RT, TSTHETA, TTHETA, TSAREA, TAREA
1630 REM _____
1640 REM * BOTTOM SURFACE (COMPLEX) GEOMETRY DESCRIPTION *
1650 REM -------------------------------------------------
1660 DIM XC(21),YC(21),ANGLE(21),ANGLE1(21),R(21)
1670 DIM XB1(22,PP), YB1(22,PP),XB(N+3),YB(N+3),RB(N+3)
1680 DIM BSTHETA(N+3),BTHETA(N+3),BAREA(N+3),BSAREA(N+3)
1690 LOCATE 8,14 : PRINT "PLEASE WAIT"
1700 LOCATE 11,10 : PRINT "CALCULATING  BOTTOM"
1710 LOCATE 14,13 : PRINT "SURFACE  DATA"
1720 DATA 1,0,.8531129,.3387312,.641536,.546, .641536,.546
1730 DATA .4082422,.6595622,.2261,.6956, .2261,.6956,
1740 DATA .0738449, .6902335,-.0306225,.5793417,-.0306225
1750 DATA .5793417, -.02690384,.4270375 0,.3826,
1755 DATA 0,.3826,.0277976, .333715, 02840379,.250094
1760 DATA .02840379,.2500941,-.04309334,.1663128,-.0696
1770 DATA .1565,-.0696 .1565,-.166,.1804,-.226,.2087,
1775 DATA -.226,.2087, -.4323,.35032
1780 DATA -.54,.4783, - 54,.4783,-.696,.515,-.8,.4869,
```

```
1790 DATA -.8,.4869,-.978,.2165,-1,0,   -1,0,-.926,-.4149,
1800 DATA -.8984189, -.4687486 -.8984189,-.4687486,
1810 DATA  -.831338,-.5701419,-.75,-.6605  -.75,-.6605,
1815 DATA  -.6422, -.7632, -.522,-.8, -.522,-.8,-.3811398
1820 DATA -.7282893,-.3478,-.626,  -.3478,-.626,-.333,
1830 DATA -.4484,-.3478 -.3304, -.3478,-.3304,-.3924,-.504
1840 DATA -.0696,-.313,  -.0696 -.313,-.00064, -.414,.034
1850 DATA -.4869, .0348,-.4869,.246,-.663 .4174,-.7304,
1860 DATA .4174,-.7304, .6938,-.698,.8348,-.5739
1865 DATA .8348,-.5739,.976,-.241,1,0
1870 FOR I = 1 TO 20
1880 READ XF,YF, XM,YM, XS,YS
1890 XF = XF*RI : YF = YF*RI
1900 XS = XS*RI : YS = YS*RI
1910 XM = XM*RI : YM = YM*RI
1920 AA = YS^2-YM^2) ((XM-XS)*((XF^2-XM^2)+(YF^2-YM^2)))+
((XF-XM)*(XS^2-XM^2+ )
1930 AB = ( (YF-YM)*(XM-XS))-((XF-XM)*(YM-YS) )
1940 YC = AA / ( 2*AB )
1950 XC = ( (XS^2-XM^2+YS^2-YM^2) + (( 2*YC)*(YM-YS))) /
(2*(XS-XM))
1960 A1 =   ( YC-YF ) / ( XC-XF )
1970 B1 = -1  : B2 = B1
1980 A2 = ( YC-YS ) / ( XC-XS )
1990 XC(I)= XC : YC(I) = YC
2000 ANGLE(I)= ATN( ( (A1*B2)-(A2*B1))/((A1*A2)+(B1*B2)) )
2010 IF XF < XC THEN 2050
2020 IF YF < YC THEN 2100
2030 ANGLE1(I) = ATN( (YF-YC) / (XF-XC)  )
2040 GOTO 2110
2050 IF YF < YC THEN GOTO 2080
2060 ANGLE1(I) = PI - ABS( ATN( (YF-YC) / (XF-XC) ) )
2070 GOTO 2110
2080 ANGLE1(I) = PI + ABS( ATN( (YF-YC) / (XF-XC) ) )
2090 GOTO 2110
2100 ANGLE1(I) = 2 * PI - ABS( ATN( (YF-YC) / (XF-XC) ) )
2110 R(I) = SQR( (XF-XC)^2 + (YF-YC)^2 )
2120 NEXT I
2130 B = 0
2140 FOR I = 1 TO 20
2150 DSY = ANGLE(I) / NP : SY = ANGLE1(I) - DSY
2160 IF I = 20 THEN NOP = NP + 1 ELSE NOP = NP
2170 FOR J = 1 TO NOP
2180 SY = SY + DSY : M = B+J
2190 XB1(I,J) = (R(I)  * COS(SY) + XC(I))
2200 YB1(I,J) = (R(I)  * SIN(SY) + YC(I))
2210 XB(M) = XB1(I,J)
2220 YB(M) = YB1(I,J)
2230 IF J = NOP THEN 2250
2240 NEXT J
2250 B = J * I
2260 NEXT I
2350 FOR I = 1 TO N+1
2360 RB(I) = SQR( XB(I)^2 + YB(I)^2 )
2370 IF I = 1 THEN GOTO 2410
2380 IF I = N+1 THEN GOTO 2450
2390 IF XB(I) < 0 THEN 2430
2400 IF YB(I) =< 0 THEN 2450
```

```
2410 BTHETA(I) = ATN( YB(I) / XB(I) )
2420 GOTO 2460
2430 BTHETA(I) = PI + ATN( YB(I)/XB(I) )
2440 GOTO 2460
2450 BTHETA(I) = (2*PI) + ATN( YB(I)/XB(I) )
2460 BSTHETA(I) = BTHETA(I) - BTHETA(I-1)
2470 IF I = 1 THEN RB(0) = RB(1)
2480 RB1 = ( RB(I) + RB(I-1) ) / 2
2490 BSAREA(I) = ( RB1^2*BSTHETA(I) ) / 2
2500 BAREA(I) = BAREA(I-1) + BSAREA(I)
2510 P = XB(I) : GOSUB 3480 : XB = VAL(P$)
2520 P = YB(I) : GOSUB 3480 : YB = VAL(P$)
2530 P = RB1 : GOSUB 3480 : RB1 = VAL(P$)
2540 P = BTHETA(I)*RD:GOSUB 3480:BTHETA  = VAL(P$)
2550 P = BSAREA(I) · GOSUB 3480 : BSAREA = VAL(P$)
2560 P = BAREA(I)   : GOSUB 3480 : BAREA  = VAL(P$)
2570 PRIN " |"I;TAB(9);XB;TAB(20);YB;TAB(30);RB1;TAB(40);
BTHETA;TAB   (52);BSAREA;TAB(63);BAREA;TAB(74)"| "
2575 IF I = N+1 THEN 2590
2580 NEXT I
2590 PRINT": _____
2600 PRINT
2610 PRINT "TOTAL AREA OF THE BOTTOM SURFACE (COMPLEX AT
Z=0) =",BAREA(I); "mm Square." : PRINT
2620 PRINT "REDUCTION RATIO AT THE BOTTOM SURFACE AREA
=";((TAREA-BAREA)*100)/TAREA;"%"
2630 PRINT "-----------------------------------------------
```

4.4. GEOMETRIC DESCRIPTION FOR THE EXTRUSION DIE

The geometric description for an extrusion die is
carried out in three stages. In each stage the circle
geometry is described for both the surfaces for different
sizes. The X and Y co-ordinates are calculated for each
circle by using the trigonometric functions of SIN and COS,
like the circle shape described in topic 4.3.1. The number
of points and sizes for circles are user selected. All the
points calculated in three stages are equidistant from each
other for each section. The software developed for
geometric description of three stages is given in Appendix

C2. The calculations for all three stages for the top surface start at line number 1310 and for the bottom surface, at line number 1700.

In the first stage, a small hole circle geometry is described having the same radii for the top and bottom surfaces. The points connecting the top and bottom surfaces having the same angles at the corresponding surfaces and the first points for both the surfaces are described at zero degree and the last points at 360°. It means that the first stage describes the geometry of the same circle at top and bottom surfaces. The first stage is shown in **figure 61** by the smaller dotted lines.

In the second stage, the geometry description for the top and bottom surfaces is different from that in the first stage. A bigger circle geometry is described at the top surface and a smaller circle geometry is described at the bottom surface. The first point calculated for the top surface in second stage is at 0° and the final point at 360°. The first point for the bottom surface geometry is calculated at 180°. By connecting all these points between the top and bottom surface at 180° of rotation for each point a bigger circle at the top and a smaller circle at the bottom surface are formed having a narrower passage nearer the bottom surface. The second stage is shown in **figure 61** by small dashed lines.

In the third stage, the geometry is described in the

same way as in the second stage. The difference is that only the sizes of the circles at both the surfaces are slightly bigger than in the second stage. The stage three geometry is represented in **figure 61** by the continuous lines.

First point for all the three stages for the top surface start at zero degree (REFER STATEMENT 1310-1330 Appendix C2).

XT = ROT * COS (SY)   (REFER STATEMENT 1340 APPENDIX C2)

YT = ROT * SIN (SY)   (REFER STATEMENT 1350 APPENDIX C2)

where **ROT** is the user selected Radius Of Top circle.

For the bottom surface data calculations, program first decides stage for which the data is being calculated. If the stage is number one then the first co-ordinate data calculations start from zero degree, otherwise, the first co-ordinate data calculations start at 180°. (REFER STATEMENT 1700-1740 and 1830 Appendix C2).

XB = ROB * COS (SY)   (REFER STATEMENT 1840 APPENDIX C2)

YB = ROB * SIN (SY)   (REFER STATEMENT 1850 APPENDIX C2)

Where **ROB** is the user selected Radius Of Bottom circle.

The equations used for calculating the resultant distance of X and Y co-ordinates at the boundary of the profile for each point, angles between the two points and the area are the same as described in topic 4.3.1. A few conditional statements are added for the bottom surface area calculations in the last two stages to start the area calculations from 180° rather than from 0°. The display of the calculated data is also carried in the same way.

After each stage data calculations the program branches to other 'CONTROL.BAS' (Appendix C9) program which generates the same holes and then comes back to this program to carry out the tasks for the next stage until all the three stages are fully generated.

4.5. GEOMETRIC DESCRIPTION FOR CIRCLE TO CRESCENT SHAPE

The software develped to describe the geometry of a circle shape at the top surface and crescent at the bottom surface at any known distance from each other is given in volume II, Appendix C3.

The geometrical description for the circle shape is calculated by dividing the circle into two parts. The first part calculates the X and Y co-ordinates, the resultant and the angles of the points in the plane for a user selected number of points on the profile upto 250° to match the co-ordinate locations for the bottom surface data. The second part calculates the same data on the

remaining arc of the circle from 250° to 360°. This top surface calculations start at line number 1150 in Appendix C3. The program then displays the same data on the screen including the sector area and the total area enclosed by the circle profile in the same way as described in previous sections.

The crescent shape description is carried out in two parts. The first part determines the X and Y co-ordinates of the outer edge of the crescent. The second part calculates the co-ordinates of the inner edge of the crescent. The starting point at the corner of the crescent is kept at 0° and the other corner of the crescent is decided to be kept at 250°, which gives a better shape for the crescent. The software describing the geometry for the crescent shape is referred to **figure 62**.

The co-ordinates for the outer edge of the crescent are calculated in a loop at line number 1740 for half the number of user selected points. The X and Y co-ordinates of the outer edge of the crescent are calculated by using the same procedure as for the circle shape (REFER STATEMENT 1760 AND 1770 Appendix C3), where **RB** is the user selected radius of outer the edge arc and **SY** is the incremental angle for each point to be calculated.

For finding out the co-ordinates of the inner edge of the crescent the centre point co-ordinates of the edge to be determined and it's location needs to be decided. The

software geometry description for the crescent shape is extracted from Appendix C3, and is shown at the end of this topic. By refering to **figure 62**, the co-ordinates of the outer edge are known for the first corner **A** and for the corner **B** . Therefore from figure 62, the value of the angle **THETA** will be equal to

$$\mathbf{THETA} = \tan^{-1} \left(\frac{YB(1) - YB(I-1)}{XB(1) - XB(I-1)} \right)$$

(REFER STATEMENT 1800 APPENDIX C3)

Hence, the length **AB** will be equal to

$$\mathbf{AB} = \sqrt{(XB(1)-XB(I-1))^2 + (YB(1)-YB(I-1))^2}$$

(REFER STATEMENT 1810)

Therefore X and Y co-ordinates of point L as a mid point of point A and B will be

$$\mathbf{XL} = ((AB/2) * \cos(\theta)) + XB(I-1) \quad \text{(REFER STATEMENT 1820)}$$

$$\mathbf{YL} = ((AB/2) * \sin(\theta)) + YB(I-1) \quad \text{(REFER STATEMENT 1830)}$$

The length of the line **OL** will be equal to

$$\mathbf{OL} = \sqrt{XL^2 + YL^2} \qquad \text{(REFER STATEMENT 1840)}$$

Now the angle α of line OL can be calculated as

$$\alpha = (2 * \pi) + \tan^{-1}(YL/XL) \quad \text{(REFER STATEMENT 1850)}$$

For the inner edge the centre was decided to be at the mid point **C** of line OL. Therefore the co-ordinates of point **C** will be.

$$X_C = (OL/2) * \cos(\alpha) \qquad \text{(REFER STATEMENT 1860)}$$

$$Y_C = (OL/2) * \sin(\alpha) \qquad \text{(REFER STATEMENT 1870)}$$

Therefore radius **RB1** for the inner edge of the crescent will be equal to

$$RB1 = \sqrt{(XB(1) - XC)^2 + Y_c^2} \qquad \text{(REFER STATEMENT 1880)}$$

Now, the angles which, points **A** and **B** are making with the centre **C** of the inner edge of the crescent need to be known, as the initial and final angles for the X and Y co-ordinates to be calculated. The initial angle β and final angle β1 will be

$$\beta = \pi + \tan^{-1}(\ (YB(I-1)-Y_c) \ / \ (XB(I-1)-X_c) \ )$$
(REFER STATEMENT 1890)

$$\beta1 = \tan^{-1}(\ (YB(I-1)-Y_c) \ / \ (XB(I-1)-X_c) \ )$$
(REFER STATEMENT 1900)

Once the radius (**RB1**), start angle (β), and final angle (β1) are known, then the X and Y co-ordinates of the inner edge of the crescent can be found by using simple trigonometric functions (REFER STATEMENT 1910-1970)

The area claculations are carried out in the same way as in the previous sections. The only difference here is that the area enclosed by the inner edge of the crescent is to be subtracted from the area enclosed by the outer edge of the crescent (see **figure 63**). This calculated data is shown in **table 9**. The reduction ratio in area at this surface shown at the end of the table is calculated by assuming the radius of the top surface as 20 mm (AREA = 1256.637 mm²).

```
1720 DSY = (500*DR)/N
1730 SY = 0 : SY= SY - DSY
1740 FOR I = 1 TO (N/2)+1
1750 SY = SY + DSY
1760 XB(I) = RB *COS(SY)
1770 YB(I) = RB *SIN(SY)
```

```
1780 NEXT I
1790 '---------------------------------------------
1800 THETA = ATN((YB(1)-YB(I-1)) / (XB(1)-XB(I-1)))
1810 AB = SQR(  (XB(1)-XB(I-1))^2 + (YB(1)-YB(I-1))^2)
1820 XL= ((AB/2)*COS(THETA)) + XB(I-1)
1830 YL= ((AB/2)*SIN(THETA)) + YB(I-1)
1840 OL =  SQR(XL^2+YL^2)
1850 ALFA= (2*PI) + ATN(YL/XL)
1860 XC = (OL/2) * COS(ALFA)
1870 YC = (OL/2) * SIN(ALFA)
1880 RB1 = SQR((XB(1)-XC)^2 + YC^2)
1890 BETA = PI + ATN( (YB(I-1)-YC)/(XB(I-1)-XC)  )
1900 BETA1= ATN( (YB(1)-YC)/(XB(1)-XC)  )
1910 DSY = (2*(BETA-BETA1)) / N
1920 SY = BETA
1930 FOR I = ((N/2)+2) TO N+1
1940 SY = SY - DSY
1950 XB(I) = (RB1 * COS(SY)) + XC
1960 YB(I) = (RB1 * SIN(SY)) + YC
1970 NEXT I
1980 '---------------------------------------------
```

4.6. GEOMETRIC DESCRIPTION FOR THE CIRCLE / PRISMATIC TO CIRCLE / PRISMATIC SHAPES

The software developed to describe the circle or prismatic (square/rectangle) shapes can defined any of the geometry on either of the surfaces for the workpiece of different sizes for user selected number of points and sizes. This software is given in volume II Appendix **C4**.

This program firstly asks, what shape geometry is intended to be described at both the surfaces of the workpiece. The program branches to different sub-routines to find the X and Y-axes co-ordinates for the user selected shape and sizes. The geometry for the circle shape is described in the same way as carried in the previous sections. The only difference here is that , the first point calculations start at 45° rather than at 0° as in the

other software described before. For a top surface as a circle shape geometry description loop is extracted from Appendix C4 and is shown below. Where **ROT** is the user selected radius of the top surface.

```
1510 IF ST$="1" THEN 1520 ELSE 1590
1520 DSY = (2*PI)/N · SY = SY - DSY
1530 FOR I=1 TO N+1
1540 SY = SY + DSY
1550 XT(I) = (ROT * COS (SY+(45)*DR))
1560 YT(I) = (ROT * SIN (SY+(45)*DR))
1570 NEXT I
```

The other data, resultant, angles, sector area and total area is also displayed in the same way. (REFER THE LOOP GIVEN AT LINE NUMBER 2130 APPENDIX C4).

The co-ordinates describing the square/rectangle shape are obtained by dividing the total number of points assigned to the four sides of the shape. This can be seen in line number 1190 (Appendix C4), where C is the length of the shape along X-axis and D is the length of the shape along Y-axis. The calculations to determine the X and Y co-ordinates for the bottom surface as a prismatic shape start at line number 1830.

There are four loops starting at line number 1860, 1890, 1920 and 1950 ,Appendix C4 which calculate the co-ordinates along the four sides to form a prismatic shape. The N variable is the total number of points of the shape. These four loops are also extracted from Appendix C4 and are given at the end of this topic.

The first loop determines the co-ordinates for a horizontal line in quadrant I and II. The Y- co-ordinates are kept constant at value of (N/2) for (N/4) times and X co-ordinates are calculated by an expression ⟍

$$XB = (\ \frac{(C)}{2} - (\ \frac{(4C)}{N}\ ) * (\ I-I)))$$

The second loop determines the co-ordinates of a vertical line in II and II quadrants. The Y- co-ordinates are kept constant for this line at a value of - (C/2) for (N/4) times. The Y co-ordinates are calculated by an expression

$$YB = \frac{(D)}{2} - (\ \frac{(4D)}{N}\ ) * (I - (\frac{N}{4} + 1)))$$

The co-ordinates for another horizontal line in III and IV quadrants are calculated by keeping Y- co-ordinates constant at value of - (D/2) and X- co-ordinates are calculated by the expression.

$$XB = - \frac{(C)}{2} + (\ (\frac{4C}{N}) * (I - (N/2) + I)))$$

The co-ordinates for the last line, which encloses the prismatic shape are defined by keeping the X-axis co-ordinates constant in IV and I quadrants by the Value of (C/2) and the Y-axis co-ordinates are calculated by an expression of

$$YB = - \frac{(D)}{2} + (\ (\frac{4D}{N}) * (\ I - (\frac{(3N)}{4}) + I))$$

After calculating the X and Y- co-ordinates, the program calculates the resultant and angles each point is making with reference to 0 , and also finds out the total area at the bottom surface including the reduction ratio of area with respect to the top surface area. All these are then displayed in the same manner as in previous programs (REFER THE LOOP STARTS AT LINE NUMBER 2590 APPENDIX C4).

If the top surface is chosen as a prismatic shape, the program calculates all the data in the same manner. This calculation can be seen at line number 1590 Appendix C4).

```
1830 C1=C/2   : D1=D/2
1840 N2=FIX(N/4)
1850 PX0=C/N2 : PY0=D/N2
1860 FOR  I=1 TO (N2+1)
1870 YB(I)=D1 : XB(I)=INT (C1-(PX0 *(I-1)))
1880 NEXT I
1890 FOR I=N2+1 TO (2*N2) +1
1900 XB(I)=-(C1) : YB(I)=INT(D1-(PY0*(I-(N2+1))))
1910 NEXT I
1920 FOR I=(2*N2)+1 TO (3*N2) +1
1930 YB(I)=(-D1) : XB(I)=INT(-(C1)+(PX0*(I-(2*N2+1))))
1940 NEXT I
1950 FOR I=(3*N2)+1 TO (4*N2)+1
1960 XB(I)=(C1) : YB(I)=INT(-(D1)+(PY0*(I-(3*N2+1))))
1970 NEXT I
```

4.7. GEOMETRY DESCRIPTION FOR MANUALLY INPUT DATA, BUILT-IN DATA AND CALCULATED DATA SHAPES

There are four other programmes which have been developed, in which the data co-ordinates for both the surfaces are not calculated mathematically, as in previously described software. The X and Y co-ordinate data for one or both the surfaces are built-in for three of the different shapes at the top and/or bottom surfaces. The

fourth software developed, allows the user to manually input the X and Y co-ordinate data for both the surfaces through the keyboard for 3-D cavity to be manufactured.

The software describing the square shape at the top surface and complex shape at the bottom surface has been developed, such that the top surface data is built in within the program, and the bottom surface data is calculated. This software is shown in Appendix **C5**. The data representing the square shape is given at line number 1080 - 1190, at unit scale of one for 80 number of points. A few of the points which are built-in, are closer to each other than other points on the profile. The reason for this is to avoid the intermediate section profile shadowing the bottom surface profile.

The complex shape at the bottom surface is described in the same way as it is described in topic 4.3.2 for 80 number of points. The calculated data, the resultant distance between each point on the boundary of the profile and the centre of the complex shape , angles between two corresponding points and between each point and the reference zero, total areas at each surface including reduction ratio of the area at the bottom surface is described in the same way as in previously described software.

The software describing two squares at the both surfaces at 90° of rotation is given in Appendix **C6**. The

data for both the surfaces are built into the program for 80 points at unit scale of one. The magnification is selected and can be increased up to 40. The bigger magnification can not be machined on the present manipulator. Other data calculations are carried out in the same way as described for other geometries and are displayed in the same manner as well.

The software describing the circle shape at the top surface and the star shape at the bottom surface is given in Appendix C7. The circle shape is described in the same way as in topic 4.6, the only difference is that the first point calculations start at 0°. In total 80 points are calculated for the circle shape. All other data calculations are also carried out in the same way and displayed in the same manner. All these calculations tart at line number 1080 in Appendix C7.

The data for the star shape is built-in within the program for 80 points at unit scale of one. This data can be seen at line number 1540 - 1690 in the same Appendix C7. The Rest of the data calculations are done by using the same equations as for programs described previously. Thus all the data can be displayed including reduction ratio of the area at the bottom surface.

4.7.1. MANUAL INPUT DATA GEOMETRY DESCRIPTION

The software for Manual Data Input (MDI) mode is

developed to make 3-D die cavities other than those described above by manually inputting the X and Y co-ordinates for the top and bottom surfaces for user selected number of points, shape size and workpiece thickness. This software is shown in Appendix **C8**. The program also allows the user to read data from a disk file. If the data is going to be read from a diskfile, then the first number in the disk data file should contain the workpiece thickness (**ZT**), and the second number as the number of points (**N**) of the data saved in the file. The rest of the data in the file should contain the co-ordinates of **N** number of points for both surfaces in a format of XB, YB, XT and YT. Where XB and YB are at the bottom surface co-ordinates and XT and YT are the top surface co-ordinates for the corresponding number of points on both the surfaces.

If desired, the data which are manually fed-in by the key board can be saved in a user selected file name for further use. After reading the data from a disk file or fed through key board, the program carries out calculations for other data and displays them as described in previous programs.

Software by inputting the data manually or fed in from the disk file, has proved to be very satisfactory. **Plate 5** shows a photograph of 'straight side cross' to 'curved side cross' shape have been generated by manually inputting the data for 80 points

at the workpiece thickness of 49 mm.

4.8. GEOMETRIC DESCRIPTION FOR 3-D INTERMEDIATE SECTIONS

All the software developed the 3-D die cavities can also calculate the data for the intermediate section, area and reduction ratio of the area at any stage between the specified thickness of the workpiece. The corresponding intermediate sections can also be drawn on the screen including the top and bottom surfaces and then separately showing the area enclosed by any of the surface.

The intermediate area calculations are done because of two reasons. Firstly, to confirm the accuracy of area calculations for any intermediate section by calculating the top and/or bottom surface areas again, which is already calculated. Secondly, by knowing the area of the top surface (inlet) and bottom (outlet) as of any intermediate section, the reduction ratio of area can easily be calculated. Knowing the reduction ratio in area is very important for the drawing dies to be manufactured according to the recommended reduction ratios, which results in longer die life, and good quality product. The calculations for intermediate section data is given within the corresponding 3-D software. The flow chart for all the 3-D intermediate sections is given at the begining of Appendix C9.

A sub-routine for finding out the data for

intermediate sections is extracted from Appendix C1 and is given at the end of this topic, which shows the way, these calculations are carried out. A printout of an intermediate section calculations is given in **table 10** for the circle to complex shaped die at the Z co-ordinate value of 10 mm.

If it is assumed that the top and bottom surfaces of the 3-D shape are two co-axial circles as shown in **figure 64** then by taking a section along the die in the Z-direction such as A-A, it can be seen that by drawing a vertical line parallel to Z-axis, there will be two triangles, see **figure 65** (shadow triangles)

From geometry

$$\frac{Xt - Xb}{Zt - Zb} = \frac{XI - Xb}{ZI - Zb}$$

$$\frac{Yt - Yb}{Zt - Zb} = \frac{YI - Yb}{ZI - Zb}$$

Therefore

$$XI = Xb + \frac{(Xt-Xb)\ (ZI-Zb)}{(Zt-Zb)} \qquad \text{(REFER STATEMENT 3080)}$$

$$YI = Yb + \frac{(Yt-Yb)\ (ZI-Zb)}{(Zt-Zb)} \qquad \text{(REFER STATEMENT 3090)}$$

where

Xb and Yb are bottom surface co-ordinates,

Xt and Yt are top surface co-ordinates,

XI and YI are intermediate surface co-ordinates.

- 199-

After calculating the top, bottom and intermediate co-ordinates each 3-D software, draws the profiles in one screen. An example of such a printout for the circle to complex shape, at the top, bottom and a number of intermediate sections for 80 points is shown in **figure 66**. Each of the programs for 3-D shapes then draws the top, bottom and intermediate sections separately showing the area enclosed by each surface at the corresponding Z co-ordinate. Finally each of the software draws the top and bottom surfaces in 2-D and shows the wire cutting path between the top and bottom surfaces including the locations of the corresponding points on both the surfaces. **Figure 67** shows the wire cutting path and the location of points at both the surfaces for the circle to complex shape for 80 number of points.

```
3010 PRINT"CALCULATIONS FOR INTERMEDIATE SURFACE"I"STARTS
3020 PRINT "*******************************************
3030 PRINT"_____
3040 PRINT "Serial",TAB(12);"X";I;TAB(23);"Y";
;I;TAB(29)"RESULTANT
TAB(42)"THETA"TAB(50);"SECTOR AREA";TAB(64)"TOTAL AREA :"
3050 PRINT"|Number",TAB(11)"(mm)";TAB(22);"(mm)";TAB(29);
"(mm)"TAB(40)"Degrees)";TAB(52)"(mm Sq)";TAB(65)"(mm Sq.
)";TAB(74)"|"
3060 PRINT"|---------------------------------------
3070 FOR J = 1 TO N+1
3080 XI(I,J)=XB(J) + ((XT(J)-XB(J))*(ZI(I)-ZB)) / (ZT-ZB)
3090 YI(I,J)=YB(J)+((YT(J)-YB(J))*(ZI(I)-ZB))  /  (ZT-ZB)
3100 RI(I,J) = SQR( XI(I,J)^2 + YI(I,J)^2 )
3110 IF J = 1 THEN GOTO 3150
3120 IF J = N+1 THEN GOTO 3190
3130 IF XI(I,J) < 0 THEN 3170
3140 IF YI(I,J) < 0 THEN 3190
3150 ITHETA(I,J) = ATN( YI(I,J) / XI(I,J) )
3160 GOTO 3200
3170 ITHETA(I,J) = PI + ATN( YI(I,J)/XI(I,J) )
3180 GOTO 3200
3190 ITHETA(I,J) = (2*PI) + ATN( YI(I,J)/XI(I,J) )
3200 ISTHETA(I,J) = ITHETA(I,J) - ITHETA(I,J-1)
3210 IF J = 1 THEN RI(I,0) = RI(I,1)
3220 RI1 = ( RI(I,J) + RI(I,J-1) ) / 2
3230 ISAREA(I,J) = ( RI1^2*ISTHETA(I,J) ) / 2
```

```
3240 IAREA(I,J) = IAREA(I,J-1) + ISAREA(I,J)
3250 P = ITHETA(I,J)*RD:GOSUB 3480:ITHETA  = VAL(P$)
3260 P = IAREA(I,J)  · GOSUB 3480 : IAREA  = VAL(P$)
3270 P = ISAREA(I,J) : GOSUB 3480 : ISAREA = VAL(P$)
3280 P = XI(I,J) : GOSUB 3480 : XI = VAL(P$)
3290 P = YI(I,J) : GOSUB 3480 : YI = VAL(P$)
3300 P = RI1 : GOSUB 3480 : RI1 = VAL(P$)
3310 PRINT "|"J;TAB(9);XI;TAB(20);YI;TAB(30);RI1;
TAB(40);ITHETA;TAB(52);ISAREA;TAB(63);IAREA;TAB(74)"|"
3320 IF J = N + 1 THEN 3340
3330 NEXT J
3340 PRINT":_____
3350 PRINT
3360 PRINT "TOTAL AREA OF THIS INTERMEDIATE SURFACE (AT Z
=";ZI(I);") =";IAREA(I,J);"mm Square."
3370 PRINT "-------------------------------------------
3380 PRINT "REDUCTION RATIO OF AREA AT THIS SURFACE
="((TAREA-IAREA (I,J))*100)/ TAREA;"%"
3390 PRINT "------------------------------------------
3400 PRINT "REDUCTION RATIO OF AREA AT BOTTOM SURFACE
=";((TAREA-BAREA)*100)/TAREA;"%"
3410 PRINT "------------------------------------------
```

4.9. PATH PLANNING FOR DIE GENERATION

The path planning for generating the 3-D die cavities
by controlling the 4-axes precision manipulator, is
referred to the planning of a practical path for the
workpiece to be manipulated for the cutting wire, so that
after each linear and angular movement the desired cavity
can be achieved without any overcut or undercut.

The path planning also covers the parameters such as
calculating machining area and machining time at particular
workpiece feedrate. The software developed for path
planning is given in Appendix C9 from lines 5390 to 6760.

The loop starts at line number 5390, calculates the
angles alpha and beta around the X and Y-axes respectively.

These angles are found by connecting the bottom surface points with the corresponding top surface points, which form a spline in space.

$$\alpha 1 = \tan^{-1} \left(\frac{YT - YB}{ZT} \right) \quad \text{(REFER STATEMENT 5400)}$$

$$\beta 1 = \tan^{-1} \left(\frac{YT - YB}{ZT} \right) \quad \text{(REFER STATEMENT 5400)}$$

As part of pre-planning it was decided to start machining from the centre of the workpiece for all the 3-D shapes and each point to be machined for both the surfaces is referenced to the absolute zero position (centre of workpiece).

4.9.1. CALCULATING THE TRANSFORMATION OF COORDINATES

As the base of the workpiece was kept along the plane containing the lines of rotation around the X and Y axes. By rotation of any angle, all co-ordinates for the top and bottom surfaces are changing with each rotation. For compensating the error occured for angles and linear distances, all new rotated co-ordinates and angles are calculated within the same loop. The extracted loop from Appendix C9 is given at the end of this topic.

Figure 68a shows the Y-Z plane of the rotating co-ordinates for a single rotating point by the angle alpha. By referring to figure 68a, which shows the

rotating co-ordinate according to alpha1 angle, the Y co-ordinate YB for the bottom surface changes it's position to YB1 according to the equation,

YB1 = YB * Cos (α1)

(REFER STATEMENT 5420 APPENDIX C9)

The Z co-ordinate of the same point at the bottom surface changes from zero to new value according to the following equation

ZB1 = YB * Sin (α1)

(REFER STATEMENT 5430)

Now the length of a line in Y-Z plane between the top and bottom surface is equal to

RSLT = $\sqrt{(YT-YB)^2 + ZT^2}$ (REFER STATEMENT 5440)

The Z co-ordinate for the point at the top surface will be equal to

ZT1 = ZB1 + RSLT

(REFER STATEMENT 5450)

Figure 68b shows the same, co-ordinates of the single point after rotation by α1, from X-Z plane.

Here we need to align the co-ordinate XB to XB1 by a rotation of angle, equal to β3, therefore,

$$\beta3 = \tan^{-1} \left(\frac{XT - XB}{ZT1 - ZB1} \right)$$

(REFER STATEMENT 5470)

As the XB co-ordinates, changed its position upwards by the magnitude of ZB1 in the Y-Z and in X-Z plane by an angle of β2, which is equal to

$$\beta2 = \tan^{-1} \left(\frac{ZB1}{XB} \right)$$

(REFER STATEMENT 5460)

Therefore the new XB1 co-ordinate will be equal to

XB1 = XB * Cos (ß2 + ß3)

(REFER STATEMENT 5480 - 5490)

The program now has calculated the new co-ordinates for the bottom surface (XB1, YB2) and new angles alpha1 and beta3 , after corresponding rotation for each point. As the new linear and rotary distances are calculated, which will be assigned to the corresponding points for manipulating the workpiece. Therefore, any angular movement which might be causing damage to the manipulator/cutting wire/workpiece must be checked. This checking is carried out from line numbers 5550 to 5610 The checking for angular limitations carried out in line numbers 5550 to 5610 is described in Chapter two.

After these checking are satisfactorily confirmed the program changes these new linear co-ordinates and angular movements into motor steps. This loop is also given at the end of this topic and starts at line number 5930 Before changing the distances into motor steps, it should and must be planned as to what operating mode of PC23 indexer is going to be used. If absolute operating mode is desired, then the motor steps should also be calculated in absolute fasion for all the distances. Otherwise each new distance value will be treated as in normal mode. For linear motion the lead

screws having a pitch of 1.5 mm. Therefore the absolute linear distances with respect to zero (centre of workpiece) of XB1 mm and Yb1 mm into motor steps will be

M1 = FIX (5000/1.5) * XB1

(REFER STATEMENT 5940)

M2 = FIX (500/1.5) * YB1

(REFER STATEMENT 5959)

The basic function Fix is used, so that the whole integer number of motor steps can be achieved. Motor number 3 and 4 are dedicated to rotary motion (beta and alpha motions) and are attached with the gear boxes having gear ratios of 18:1 and 100:1 respectively.

Therefore the absolute angles alpha and beta in motor steps will be equal to

$$\textbf{Alpha} = M4 = \frac{(100 * 5000)}{360} * \text{alpha1}$$

(REFER STATEMENT 5970)

$$\textbf{Beta} = M3 = \frac{(18 * 5000)}{360} * \text{beta3}$$

(REFER STATEMENT 5960)

The backlash of one degree in motor three is compensated by an addition of line 5980 - 6050. Number 250 motor steps are equal to one degree for motor three having a gear ratio of 18:1.

```
5390 FOR I = 1 TO N+1
5400 ALFA1(I) =   ATN( (YT(I)-YB(I)) / ZT )
5410 BETA1(I) =   ATN( (XT(I)-XB(I)) / ZT )
5420 YB1(I) = YB(I) * COS( ABS(ALFA1(I)) )
5430 ZB1(I) = YB(I) * SIN ( ALFA1(I) )
5440 RSLT(I) = SQR( ABS( (YT(I)-YB(I))^2 + ZT^2 ) )
5450 ZT1(I) = ZB1(I) + RSLT(I)
5460 BETA2(I) = ATN( ZB1(I)/XB(I) )
5470 BETA3(I) = ATN( (XT(I)-XB(I)) / (ZT1(I)-ZB1(I)) )
5480 BETA4(I) = BETA2(I) + BETA3(I)
5490 XB1(I) = XB(I)  * COS( ABS(BETA4(I)) )
```

```
5500 IF ZT>72 AND (ALFA1(I)*RD)<-30 THEN BEEP:GOTO 5650
5510  'W.P. protection from being in touch with upper
5520  'support bar of  main beam
5530 IF ZT > 50 AND (ALFA1(I)*RD)<((6+(ATN(60/ZT)*RD))-90)
THEN BEEP:GOTO 5650
5540  'W.P. protection from being in touch with Mx10 HCSH
screw.
5550 IF (YT(I)-YB(I)) < 0 AND (ALFA1(I)*RD) < ( (ABS((
ATN(17.5/(60    YB(I)))*RD))-90) THEN BEEP : GOTO 5650
5560 'Protection of wire being in touch with inner frame
for maximu   negative Alfa
5570 IF (ALFA1(I)*RD)>(90-( ATN(17.5/(60-YB(I))))) THEN
BEEP :    GOTO 5650
5580 'Protection of wire being in touch with inner frame
for   maximum positive Alfa.
5590  IF (XT(I)-XB(I)) < 0 AND (BETA3(I)*RD) < -50 THEN
beep : GOTO 5700
5600  'Protection of motor being in touch with table
(Base) at  Max. negative Beta.
5610 IF (BETA3(I)*RD) > ( 90-((ATN(17.5/(50-XB(I))))) *RD))
THEN  BEEP :GOTO 5700
5620  'Protection of wire being in touch with inner frame
at  Max. positive  Beta.
5630 NEXT I
---------------------------------------------------------
5930 FOR I = 1 TO N+1
5940 M1(I) = FIX((5000/1.5) * XB1(I))
5950 M2(I) = FIX((5000/1.5) * YB1(I))
5960 M(I)=FIX(((18 * 5000)/360 )*(BETA3(I)*RD)):M(I)=-M(I)
5970 M4(I) = FIX(((100 * 5000) / 360 ) * (ALFA1(I)*RD))
5980  IF I =  1 THEN GOTO 6050
5990  IF M(1) < 0   THEN GOTO 6040
6000  IF M(1) > 0   THEN GOTO 6020
6010  IF M(1) = 0 AND M(2) < 0 THEN GOTO 6040
6020  IF M(I)<M(I-1) THEN M3(I)=M(I)-250 ELSE M3(I)=M(I)
6030  GOTO 6060
6040  IF M(I)>M(I-1) THEN M3(I)=M(I)+250 ELSE M3(I)=M(I)
6050  IF I = 1 THEN M3(1) = M(1)
6060 NEXT I
```

4.9.2.   CALCULATING MACHINING AREA, MACHINING TIME AND

WORKPIECE FEEDRATE

By knowing the X and Y co-ordinates for the top

and bottom surfaces for each point on the die profile,

the machining area, machining time at particular

workpiece thickness and feedrate can be found. These

calculations are given in software developed in Appendix **C9** in a loop which starts at line numbers 6270. An extracted sub-routine is given at the end of this topic.

From X and Y co-ordinates the distance between two corresponding points can be known at both the surfaces as a small straight line (segment). The segment for the bottom surface between two points is equal to:

RB $= \sqrt{(XB(I) - XB(I-1))^2 + (YB(I) - YB(I-1))^2}$

Therefore the distance between two corresponding points at the top surface

RT $= \sqrt{(XT(I) - XT(I-1))^2 + (YT(I) - YT(I-1))^2}$

(REFER STATEMENTS 6280 - 6290)

By connecting two corresponding points at the bottom surface with the two corresponding points at the top surface (two splines), a trapezium shape can be formed. This is the travel for four motors to generate a small single segment at both the surfaces.

Therefore the area of this small trapezium shape can be calculated by using the following equation.

AREA $= \dfrac{(RB + RT) * ZT}{2}$

(REFER STATEMENT 6300 APPENDIX C9)

By adding all the areas of the small trapezium shapes the program calculates the total machining area for the die cavity (REFER STATEMENT 6310). The

machining area is calculated by using original co-ordinates before rotation, which is the actual machining area on the die profile. The time in which the calculated area will be machined, is the time needed to achieve the new co-ordinates position after rotation i.e. (XB1, YB1, alpha1 and beta3).

Therefore, machining time for each sector is calculated by using new co-ordinates after rotation by using simple motion equation.

$$t = S/V$$

Where t = time, S = travelling distance for each motor and V = velocity.

Now, by referring to statement 6360 Appendix **C9**, the incremental distance between two points at the bottom surface will be equal to:

$$S = \sqrt{XA^2 + YA^2} \qquad \text{and} \qquad H = Area / S$$

Where XA and YA are the incremental distances between two points along X and Y axes for the bottom surface (refer statements 6320 and 6330). The **H** variable calculated, is used to know the linear distance by dividing the area of the corresponding trapezium with the incremental resultant distance S, of the X and Y axes at the bottom surface.

Therefore, the machining time for each segment is calculated by using the following equation.

$$TM = \frac{S}{(FR/(H*60))}$$

(REFER STATEMENT 6370)

Where **FR** is the user selected workpiece feedrate in mm^2/min.

As it is described before in topic 4.2 that the bottom surface is the result of linear motions and the top surface is the result of angular movements, therefore, calculations of the velocity rates for linear axes are carried out by using point-to-point linear interpolation principle. The time calculated is then used to determine the velocities for angular manipulation. It means that within the same time according to the selected workpiece feedrate the calculated area of a small trapezium can be machined. As a result a small segment can be formed at both the surfaces for a pre-described shape.

The velocities for linear axes are calculated by the following equations.

$$VR^2 = \sqrt{VX^2 + VY^2} \qquad (4)$$

Where

VX = Velocity along X axis

VY = Velocity along Y axis

VR = Resultant Velocity

The ratio of distances between X and Y axes is equal to:

$$\mathbf{RTO} \; = \; (YA/XA)$$

(REFER STATEMENT 6410)

Therefore

$$\mathbf{Vx} \; = \; Vy/RTO \quad \text{and} \quad \mathbf{Vy} \; = \; Vx * RTO$$

AS the user selected workpiece feedrate is being selected in mm^2/min, and the PC23 velocity commands can only be specified into revolutions per second, the workpiece feedrate needs to be changed into revolutions per second to assign this value to the PC23 indexer velocity parameter commands.

Therefore

$$\mathbf{VR} \; = \; \left(\frac{FR}{H*60} \right) * \left(\frac{1}{1.5} \right)$$

(REFER STATEMENT 6420)

Where 1.5 is the lead screw pitch and H variable is used to change the area into linear distance for the bottom surface.

Now, by substituting the value of Vy into equation (4) and simplifying we get the constant velocity value for X axis motion, according to the following equation.

$$\mathbf{Vx} \; = \; \sqrt{\frac{VR^2}{(1 + RTO^2)}}$$

(REFER STATEMENT 6470 APPENDIX C9)

The velocity term for Y axis then is simply equal to

$$\mathbf{Vy} \; = \; Vx * RTO$$

(REFER STATEMENT 6550)

- 210-

The constant velocities for incremental alpha and beta angular distances (refer statement 6340 - 6350), are calculated by using the same time (refer statement 6370), which is required for both the linear axes to complete their move at a particular workpiece feedrate between the same corresponding points.

Therefore the velocity for the rotary motion beta is

$$\mathbf{VB} = \frac{\text{Beta} * 18}{2 * \pi * \text{TM(I)}}$$

(REFER STATEMENT 6630)

where, 18 is the gear ratio of the gear box attached to this motor and 2π is used to change angle beta from radians to revolutions. The velocity value for another rotational motion alfa is calculated as:

$$\mathbf{VA} = \frac{\text{ALFA} * 100}{2 * \pi * \text{TM(I)}}$$

(REFER STATEMENT 6710)

These theoretically calculated values of alpha, beta, machining area, machining time, total machining area and total machining time can be displayed for any of the 3-D shapes described. A typical printout of these calculations for circle to complex shape for 80 points is shown in **table 11**.

```
6270 FOR I = 1 TO N+1
6280 RB(I)= SQR(((XB(I)-XB(I-1))^2) + ((YB(I)-YB(I-1))^2))
6290 RT(I)= SQR(((XT(I)-XT(I-1))^2) + ((YT(I)-YT(I-1))^2))
6300 AREA(I) = ( (RB(I)+RT(I))*ZT )/2
6310 TAREA(I) = TAREA(I-1) + AREA(I)
6320 XA(I) = XB1(I) - XB1(I-1)
6330 YA(I) = YB1(I) - YB1(I-1)
6340 ALFA(I) = ALFA1(I)-ALFA1(I-1)
6350 BETA(I) = BETA3(I)-BETA3(I-1)
6360 S = SQR(XA(I)^2 + YA(I)^2) : H = AREA(I)/S
6370 TM(I) = S / ( FR/(H*60) )
6380 MIN(I) = INT(TM(I)/60)
6390 SEC(I) = (((TM(I)/60)-MIN(I))*60)
6400 LOCATE 20,25   PRINT I
6410 RTO = ABS(YA(I) / XA(I))
6420 VR = (FR/(H*60)) * (1/1.5)
```

```
6430 K = M1(I) : B = 2
6440 IF K  < 0 THEN  B = 1
6450 D$ = MID$( STR$(K),B )
6460 S$ = MID$( STR$(1),1 )
6470 VX = SQR((VR^2) / (1+RTO^2))
6480 'TX = ABS(XA(I))/(VX*1.5) : PRINT TAB(20);TX;
6490 P = VX : GOSUB 9860 : VX$ = MID$(P$,1)
6500 CMD$(1,I) = S$+"VS"+VX$+S$+"V"+VX$+S$+"D"+D$+S$+"I"
6510 K = M2(I) : B = 2
6520 IF K < 0 THEN  B = 1
6530 D$ = MID$( STR$(K),B )
6540 S$ = MID$( STR$(2),1 )
6550 VY = VX * RTO
6560 P = VY : GOSUB 9860 : VY$ = MID$(P$,1)
6570 'TY = ABS(YA(I))/(VY*1.5)  : PRINT TAB(34);TY;
6580 CMD$(2,I)= S$+"VS"+VY$+S$+"V"+VY$+S$+"D"+D$+S$+"TS"+
S$+"I"
6590 K = M3(I) : B = 2
6600 IF K < 0 THEN B = 1
6610 D$ = MID$( STR$(K),B )
6620 S$ = MID$( STR$(3),1 )
6630 VB = (ABS(BETA(I))*18) / (2*PI*TM(I))
6640 P = VB : GOSUB 9860 : VB$ = MID$(P$,1)
6650 'TB = (ABS(BETA(I)*18)/(2*PI*VB)) : PRINT TAB(48);TB;
6660 CMD$(3,I) = S$+"VS"+VB$+S$+"V"+VB$+S$+"D"+D$+S$+"I"
6670 K = M4(I) : B = 2
6680 IF K < 0 THEN B = 1
6690 D$ = MID$( STR$(K),B )
6700 S$ = MID$( STR$(3),1 )
6710 VA = (ABS(ALFA(I)*100))/(2*PI*TM(I))
6720 P = VA : GOSUB 9860 : VA$ = MID$(P$,1)
6730 'TA=(ABS(ALFA(I))*100)/(2*PI*VA)  : PRINT TAB(62);TA
6740 CMD$(4,I) = S$+"VS"+VA$+S$+"V"+VA$+S$+"D"+D$+S$+"I"
6750 TIME(I) = TIME(I-1) + TM(I)
6760 NEXT I
```

4.10. SETTING MACHINING CONDITIONS PARAMETERS

Setting machining condition parameters for any shape to be manufactured has a very basic importance. The term "setting machining conditions" in here is referred to:

a)   Selection and construction of PC23 commands,

c)   Setting servo-motor resolutions,   and

d)   Setting voltage in the cutting wire.

The selection of appropriate PC23 indexer commands for its selected operating mode is done very carefully. The proper selection of commands is directly related to the response of the system and the quality of the product is being machined. The full list with brief description of the PC23 indexer commands is given in Appendix B8 . Most of the commands given in the appendix are not related in this particular application.

The commands selected for this particular robotic precision manipulator to generate 3-D shapes are:

VS = Sets instantaneous velocity,

V = Maintains the same Velocity of 'VS' for each new move,

D = Sets distance in motor steps,

I = Pre-calculates the move profile,

TS = Reads trigger input status,

MR6 = Sets motor resolution to 5000 steps/revolution,

MPA = Sets absolute operating mode of PC23 indexer,

MPI = Sets increamental operating mode of PC23 indexer. (This mode is used for 2-D shape of spur gear),

G = Initiate motion for any said axis,

G12 = Initiate motion for motor 1 and 2 in synchronized way.

G123 = Initiate motion for all three axes in synchronized fashion, and

O = Sets programmable outputs.

As all the commands are characters, therefore, the numbers representing the command parameter values are changed into strings by using **MID$** and **STR$** functions of GWBASIC programming language (REFER STATEMENT 6450, 6460 FOR X-AXIS APPENDIX **C9**)

The final form of fully constructed command for each axis is then given to another string variable CMD$. These commands required for X axis are given to **CMD$(1)**, for Y axis to **CMD$(2)**, for beta angle to **CMD$(3)** and for alpha angle to **CMD$(4)**. The string variable **S$** represents the axis number (1, 2 or 3), which is required to pre-fix with each command, **D$** represents motor steps, **VX$** represents the velocity value for X-axis motor, **VY$** represents the velocity value for Y-axis motor, **VB$** and **VA$** are representing the velocity values for angular motion beta and alpha respectively (REFER STATEMENT 6500,6580, 6660 and 6740). All commands used are pre-fixed with the axis number 1,2, or 3 , except command 'O'.

By adding all the areas of the small trapezium shapes the motor, **VB$** and **VA$** are representing the velocity values for angular motions beta and alpha respectively (REFER STATEMENTS 6500, 6580, 6660 AND 6740). All the commands used are pre fixed with the axis number 1,2 or 3, except the command O.

The function of '**VS**' command is to set start and stop velocity values. These will be non acceleration or

deceleration region in motion profile. The motor motion will start moving at the constant rate of the value given to this command and as it will achieve the target position, it will stop suddenly without any deceleration ramp. Any value given to command 'Vs' for the first move, will be assumed for the rest of all moves. Any new given values will be ignored. By using 'V' command followed by 'Vs' changes the above. If 'Vs' and 'V' commands are given, the same value for one segment and another value for the next, then for each next move it considers the new given value

As the 3-D die cavity is desired to be very precise, therefore the points at both the surfaces are closer to each other. By using 'VS' and 'V' command in a synchronized fashion will produce better results, than using accelerating command 'A' instead of 'Vs' command.

The instantaneous 'VS' and constant velocity 'V' values calculated are carried out in a synchronized way for all the axes as described in previous **section 4.10.2.**

The command 'D' is required to assign all distances for each point in motor steps. The value given to 'D' command is actually the target position for each motor to achieve.

The command 'I' is used at the end of all constructed commands to instruct the PC23 indexer to pre-calculate all

the required parameters and conditions, and as soon as 'motion initialization' commands are received to start motion within 2 msec.

The command 'G' is used to start motion for motor number prefixed to the command. This command is used for alpha rotational motion (motor 4), which is controlled by indexer two on axes number 3. The 'G123' command is the same as 'G' except that all three motors start motion at the same time at the velocity given by 'Vs' and 'V' command for the distance in motor steps given by corresponding command'D'.

The function of 'TS' command is to check the trigger input response. This command receives conditional signal back from the micro-switch to indicate whether it is ON or is still in OFF position. If the switch is closed the response returned to the computer will be '2:001000' followed by Return Bar (CHR$(13) (REFER STATEMENT 7290). Otherwise the response will be '2:000000' followed by a Return Bar (REFER STATEMENT 8910 APPENDEX C9). This 'TS' command is used on indexer number one axes number two (REFER STATEMENT 6580 AND 8550 APPENDIX C9).

The command 'MR6' sets motor resolution of 5000 steps/revolution for all the axes to match the motor resolution selected for the KS-drive (SEE APPENDIX B10 AND TABLE 3 IN CHAPTER 3), (REFER STATEMENTS 10080, 10100 AND 10430 - 10470 APPENDIX C9).

The command 'MPA' selects PC23 indexer operating mode as an absolute. The target position for each new move will be with reference to absolute zero position (REFER STATEMENT 10080, 10100 AND 10430 - 10470 APPENDIX C9). The mode used for 2-D shape i.e. spur gear manufacturing is incremental 'MPI' in which every segment is generated by an incremental value between two points.

The command 'O' is used to send programmable output signals to the PVR circuit. As any of the programmable output is received by the PVR, it turns another potentiometer in ON position to allow any pre-set voltage to the cutting wire (REFER STATEMENT 10430 - 10470 AND 8230 APPENDIX C9).

4.11. PC23 INDEXER COMMUNICATION INITIALIZATION AND MOTION CONTROL FOR DIE GENERATION

The motion control for the generation of the die cavity is the final and practical stage for any of the 3-D shape described and planned. Once the parameter commands for all the points on the profile for each motor are prepared then the PC-based program is ready to communicate with PC23 indexers to generate motor motions, set voltage in cutting wire and get responses back to the computer.

Before any exchange of prepared indexer command takes place, the indexers need to be reset according to their STATUS and CONTROL byte pattern. The meaning of each bit

of CB and SB is described in topic 3.4. According to the motion control program structure, as mentioned in topic 3.5, three sub-routines are developed using GWBASIC programming language. The three subroutines as described in Chapter 3 are:

i)   PC23 indexer resetting sub-routine,

ii)   PC23 'OUTPUT DRIVER' sub-routine

      (for sending commands to indexers), and

iii) PC23 'INPUT DRIVER' sub-routine

      (for receiving responses back to computer)

The development of these three sub-routines is carried out firstly by initializing different variables by assigning them hexadecimal numbers in accordance to the meaning of bit pattern of CB and SB. An extracted list of variables from Appendix C9 is given at the end of this topic. From the list of variables ADDRESS1% and ADDRESS2% are the base addresses of indexer number one and two respectively (Refer Table 2, Chapter 3). All other variable names shown resemble with the meaning of each bit in CB and SB.

```
10710 '****************************************************
10720 '********** THIS SUB-ROUTINE SETS VARIABLES. **********
10730 '****************************************************
10740 ADDRESS1% =&H300  'Base address of PC23  one (deci 768)
10750 ADDRESS2% =&H310 'Base address of PC23 er two (deci 784)
10760 INTRCLR=&H20 'This variable is for clearing Control Bit
10770 '           5 (to signal "Restart Watchdog Timer")
10780 RESTART=&H40'This variable is for clearing Control Bit 6
10790 '              (to signal "Restart Watchdog Timer")
10800 CONTROL=&H60'This is the normal state of the CB
10810 '                    (only Bits 5 and 6 are high)
10820 READY =&H17 'This is the normal state of the Status Byte
```

```
10830 '                        '            (bit 0, 1, 2 and 4 are set)
10840 HALT  =&H64  'This variable is for setting Control Bit 2
10850 '            (to signal the "Watchdog Timer" to time out)
10860 CMDRDY =&H70'THIS VARIABLE IS A MASK FOR SETTING CONTROL
10870 ' BIT 4 (to signal"Command Byte Ready in the IDB or not)
10880 RECEIVED=&HE0'This variable is  mask for setting Control
10890 '        BIT 7 (to signal "Message Received from the ODB")
10900 ODBREADY=8      'This variable is a mask for testing SB
10910 'BIT 3 (is a response waiting in the Output Data Buffer)
10920 IDBREADY = &H10  'This variable is a mask for testing SB
10930 '  4 (is the Input Data Buffer ready for a command byte)
10940 FAIL = &H20     'This variable is a mask for testing SB 5
10950 '         (has the PC23 suffered a processing  failure?)
10960 MASK=&H7F'This variable is mask for the Status byte MSB
10970 '----------------------------------------------------------
```

4.11.1. PC23 INDEXERS RESETTING AND COMMUNICATION

DEVELOPMENT

The resetting of both the PC23 indexers is carried out following the guidance from topic 3.5. The extracted subroutine from Appendix C9 for resetting PC23 indexers is given below. There are six steps involved in each sub-routine for resetting, output driver and input driver.

```
10980 '****************************************************
10990 '*"RESET SUBROUTINE" FOR BOTH PC23 INDEXER BOARDS      *
11000 '****************************************************
11010 'The following subroutine allows the "Watchdog Timer"  to
11020 'time  out, and Resets both the PC23s. Then the timer  is
11030 'restarted.  A  "GOSUB 11050" instruction will reset both
11040 'PC23 indexers
11050 BYTE1=0 : BYTE2=0 : TIMEOUT=1000    'Set timeout duration
11060   OUT ADDRESS1%+1,( HALT )    'CB 2 of PC23 No. 1 is high
11070   OUT ADDRESS2%+1,( HALT )    'CB 2 of PC23 No. 2 is high
11080 WHILE (BYTE1 AND BYTE2 AND FAIL) = 0 AND TIMEOUT > 0
11090   BYTE1=INP( ADDRESS1%+1 )        'Read SB  of PC23 No. 1
11100   BYTE2=INP( ADDRESS2%+1 )'Read Status Byte of PC23 No. 2
11110 TIMEOUT = TIMEOUT - 1 :WEND 'Repeat until timeout or fail
11120 IF TIMEOUT <= 0 THEN GOTO 11140
11130 GOTO 11150
11140 PRINT"Invalid response from either of the addresses.":END
11150 BYTE1=0 : BYTE2=0  : TIMEOUT=1000  'Set time out duration
11160   OUT ADDRESS1%+1,(RESTART)'CB 2 of PC23 No. 1 is high
11170   OUT ADDRESS2%+1,(RESTART)'CB 2 of PC23 No. 2 is high
11180 WHILE (BYTE1 AND BYTE2 AND MASK) <> READY AND TIMEOUT > 0
11190   BYTE1=INP( ADDRESS1%+1 ) 'Read Status Byte of PC23 NO. 1
```

```
11200  BYTE2=INP( ADDRESS2%+1 ) 'Read Status Byte of PC23 No. 2
11210 TIMEOUT = TIMEOUT - 1 : WEND        'Repeat until recovery
11220  OUT ADDRESS1%+1,(CONTROL)  'Restore CB of PC23 No.1
11230  OUT ADDRESS1%+1,(INTRCLR)  'Restore CB of PC23 No.1
11240  OUT ADDRESS2%+1,(CONTROL)  'Restore CB of PC23 No.2
11250  OUT ADDRESS2%+1,(INTRCLR)  'Restore CB of PC23 No.2
11260 IF TIMEOUT <= 0 THEN GOTO 11280
11270 GOTO 11290
11280 PRINT "Timeout recovering from reset!":BEEP:END
11290 FOR I=1 TO 200 : NEXT
11300 RETURN
11310 '------------------------------------------------------
```

The first step for resetting is done in line number 11060 and 11070, by sending hexadecimal value of variable HALT to both the PC23's base addresses. The second step is carried out at line number 11080 - 11110. In this step 1000 attempts are done to read SB, if there is no response from PC23 then the program ends with an error message. In step three 40 hex number, the value of RESTART is sent to both the PC23's CBs (REFER STATEMENT 11160 AND 11170). Step fourth attempts to read SB of both the indexers for 1000 until the MASK value becomes equal to the value of READY. Steps number five and six for resetting the indexers are done in the statement numbers 11220 -11250.

An "OUTPUT DRIVER" sub-routine is developed through which the program can send commands to both the indexers. The extracted sub-routine for "OUTPUT DRIVER" is given below:

```
11320 '**********************************************************
11330 '*                    "OUTPUT DRIVER"                     *
11340 '**********************************************************
11350'The following is a handshake subroutine allowing data to
11360 'be transferred from the IBM BUS to either of the PC23
```

```
11370 'indexers.  Command  string data is sent to the PC23s
11380 'one character at a  time.
11390 FOR I = 1 TO LEN( CMD$ )
11400  CHAR$ = MID$( CMD$, I, 1 )'Fetch command characters and
11410   GOSUB 11460                      'Send them one at a time
11420 NEXT I
11430   CHAR$ = CHR$(13)·GOSUB 11460
11440 RETURN
11450 '
11460 BYTE = 0:TIMEOUT = 1000                  'Set timeout duration
11470 WHILE (BYTE AND IDBREADY)=0 AND TIMEOUT>0'Ready /timeout
11480     BYTE = INP( ADDRESS%+1 )                 'Read Status Byte
11490 TIMEOUT = TIMEOUT - 1 : WEND                          'Repeat
11500 IF TIMEOUT<=0 THEN PRINT"Timeout during write!":BEEP:END
11510   OUT ADDRESS%, ASC(CHAR$)          'Write command character
11520   OUT ADDRESS%+1, (CMDRDY)        Signal charater is waiting
11530 BYTE = 255:TIMEOUT = 1000                  'Set timeout duration
11540 WHILE (BYTE AND IDBREADY)>0 AND TIMEOUT>0'Busy / timeout
11550     BYTE = INP( ADDRESS%+1 )                 'Read Status Byte
11560 TIMEOUT = TIMEOUT - 1:WEND                           'Repeat
11570   OUT ADDRESS%+1, ( CONTROL )
11580 IF TIMEOUT<= 0 THEN PRINT"Timeout after write!":BEEP:END
11590 RETURN
11600 '---------------------------------------------------------
```

The line number 11390 sets the length of command CMD$, which is being sent to either of the indexers, by using LEN function of BASIC language. The ADDRESS% variable is used here instead of ADDRESS1% or ADDRESS2%. Therefore, the ADDRESS1% or ADDRESS2% are changed to ADDRESS% before sending any command to this sub-routine. This way these sub-routines are more compact and easier to understand for other users. Step two is solved in lines 11460 - 11490 to check whether the IDB is ready or not to receive one more character from the command CMD$. Step three and four are done at lines 11510 and 11520 respectively. Step number five is carried out in lines 11530 - 11560 and step six in line number 11570 Appendix C9.

The **"INPUT DRIVER"** is used for getting responses related to motor positions, trigger input signals, PC23 buffer status and other conditions back to the computer. For getting any required response back to the computer, the corresponding command has to be sent first, through the **"OUTPUT DRIVER"**. This extracted sub-routine from Appendix C9 is shown below:

```
11610 '*******************************************************
11620 '*                    "INPUT DRIVER"                   *
11630 '*******************************************************
11640 'The following is a handshake subroutine allowing data to
11650 ' be transfered from either of the PC23 indexers to
11660 ' the IBM BUS. This data is sent one character at a time.
11670 '
11680 ANSWER$=""                          'Initialize response string
11690 BYTE = 0:TIMEOUT = 5                 'Initialize variables
11700 WHILE (BYTE AND ODBREADY)=0 AND TIMEOUT>0'Ready /timeout
11710     BYTE = INP( ADDRESS%+1 )              'Read Status Byte
11720     TIMEOUT = TIMEOUT - 1:WEND                     'Repeat
11730 IF TIMEOUT <= 0 THEN RETURN          'Give up if no message
11740 ANSWER = INP( ADDRESS% )             'Read 1 response byte
11750 OUT ADDRESS%+1,(RECEIVED)        'Signal character received
11760 BYTE = 255:TIMEOUT = 1000            'Initialize variables
11770 WHILE (BYTE AND ODBREADY)>0 AND TIMEOUT>0'Busy / timeout
11780     BYTE = INP( ADDRESS%+1 )              'Read Status Byte
11790     TIMEOUT = TIMEOUT - 1 : WEND                   'Repeat
11800 IF TIMEOUT <= 0 THEN PRINT"Timeout after read!":BEEP:END
11810 OUT ADDRESS%+1, ( CONTROL )          'Restore control byte
11820 CHAR$ = CHR$( ANSWER )               'Convert code to char.
11830 ANSWER$ = ANSWER$ + CHAR$                'Add char to answer
11840 IF CHAR$ = CHR$(13) THEN RETURN ELSE 11690
11850 '_____
```

The variable ANSWER$ is firstly initialized to null in line number 11680. Lines through 11700 to 11720 check and wait till any single response character is ready in **ODB**. In step three, the line number 11740 reads that character. In step four, by setting control bit 7, the signal is given to CB that previous character is received and a new character can be kept again. This is shown in line number 11750.

Step five of this sub-routine is described in lines 11760 - 11790, and finally sixth step is done in line 11810 Appendix **C9**.

Line numbers 11820 and 11830 add all the single characters received and assign the full response from PC23 to the string variable ANSWER$.

4.11.2. MOTION CONTROL FOR 3-D DIE GENERATION

The four axes precision manipulator is controlled in a synchronized way as described in topic 3.7.1 for generating all the 3-D die cavities for different shapes.

The sub-routine developed for synchronized motion control to generate the 3-D die cavities is also extracted from Appendix **C9** and is shown below, which in preset absolute operating mode, the last point (N+1) is the zero position where the machining starts from, and finishes (the pre-machining wire position).

```
7170  '---------------------------------------------------------------
7180  '*  FOLLOWING LOOP  CONTROL THE MOTOR MOTION AND   CHECKS
7190  '*   THE TRIGGER INPUT FROM 'PVR' CIRCUIT AFTER EACH MOVE
7200  '---------------------------------------------------------------
7210  FOR L = 1 TO N+1
7220  ADDRESS% = ADDRESS2%
7230  CMD$ = CMD$(4,L)  · GOSUB 11390
7240  ADDRESS% = ADDRESS1%
7250  CMD$ = CMD$(1,L)+CMD$(2,L)+CMD$(3,L)  :  GOSUB 11390
7260  CND$ = CMD$(1,L)+CMD$(2,L)  :  CDN$ = CMD$(3,L)+CMD$(4,L)
7270  GOSUB 8150
7280  GOSUB 11680
7290  IF ANSWER$ = "2:001000"+CHR$(13) THEN 7300 ELSE 7320
7300  TTIM = 0  :  TEM = 0  :  GOSUB 8230
7310  L = Z  :  GOTO 7220
```

```
7320 TEM = TEM + TM(L) : TMI = TTIM - TEM
7330 MIN = INT(TMI/60) : SEC = (((TMI/60)-MIN)* 60)
7340 TMS$ = STR$(MIN)+" MINUTES AND"+MID$(STR$(SEC),1,6)+"
SECONDS."
7350 TME$ = STR$(MIN(L))+" MINUTES
+"SECAND"+MID$(STR$(SEC(L)),1,6)+" ONDS."
7360 LOCATE 3,47 : PRINT TMS$
7370 LOCATE 4,47 : PRINT TME$
7380 ADDRESS%=ADDRESS2%:CMD$ = "3G":GOSUB 11390 : ADDRESS%
ADDRESS1%
7390 CMD$ = "G123"  : GOSUB 11390
7400 LOCATE 9,18:PRINT "NOW POINT NUMBER";L;"IS BEING
MANUFACTURED."
7410 LOCATE 18,12
7420 PRINT "COMMANDS SENT TO THE PC23 INDEXERS FOR POINT ";L;"
ARE
7430 LOCATE 20,10
7440 PRINT "
7450 LOCATE 21,10
7460 PRINT "
7470 LOCATE 20,10 : PRINT ;CND$ : LOCATE 21,10 : PRINT ;CDN$
7480 LOCATE 12,18:PRINT "PRESS 'R' IF WISH TO CHANGE VOLTAGE
IN THE
7490 LOCATE 13,18:PRINT "CUTTING WIRE OR TO TEST RETRACING
FACILITY
7500 Q$ = INKEY$
7510 IF Q$ = "R" OR Q$ = "r" THEN GOTO 7520 ELSE 7530
7520 GOSUB 8150 : GOSUB 10220
7530 NEXT L
```

The pre-constructed commands given to double dimensioned string variable **CMD$(n, N+1)** needs to be changed into simply CM$ string variable, to make it acceptable for **"OUTPUT DRIVER"** sub-routine for all the motor numbers **(n=1,2,3 or 4)** for all the points **(N+1)** on the die profile. The sequence of tasks for sending commands and receiving responses from PC23 indexers carried out within this sub-routine is in the following steps.

1.   Sending control commands to both the indexers,

2.   Checking that all the three motors controlled by indexer number one have completed their previous

motion,

3. Receiving trigger input status, and

4. Initiating motion for commands set in step one for motor number 4 first, then for all three motors on indexer one.

The CMD$ carrying pre-planned move parameters for beta motion is first sent to the base address for indexer two (REFER STATEMENT 7220 - 7230). Following that, the same kind of machining move parameter command CMD$ for X, Y and beta motions, is sent to indexer number one, where the trigger response 'TS' command was included in axes number two (Y axes) (REFER STATEMENT 7250, APPENDIX C9). These full commands are received by all four axes buffers. The motion initialization starts firstly for beta movement and then for three other axes, by using 'G' command and 'G123' global motion execution command (REFER STATEMENTS 7380 - 7390, APPENDIX C9)

As the command 'G123' has an advantage of synchronizing operation. The disadvantage of this command is, that the next 'G123' command cannot be sent to the indexer until the previous motor motions are not completed. Therefore another simple sub-routine was built within the program, which checks after each time 'G123' command is issued that

the corresponding motor motions are completed or not. (REFER STATEMENT 8150, APPENDIX C9), Then the program continues for the next point to be machined.

The sub-routine branches from line number 7520 to line number 10220, and allows the user to set new voltage ranges for cutting wire through the PVR by using PC23 programmable output command 'O'.

Another sub-routine branched from statement 7280 checks the response of command 'TS', whether the trigger input is activated or not. If the response of ANSWER\$ is equal to "2:001000" + CHR\$ (13), it means the micro-switch is closed and the cutting wire is not able to erode the workpiece, which caused the trigger input to be activated. At this condition the program branches to another sub-routine for retracing the workpiece on the same die profile till the wire gets back to vertical position and the micro switch opens. Before retracing starts, the program completes the preset move in which the trigger input was encountered, so that the geometrical description distances can be kept constant. The program also stops the power supply to cutting wire before retracing operation takes place.

4.11.2.1. REVERSE DIE PROFILE MOTION CONTROL

The retracing motion control for a fixed geometry description using the absolute operating mode, at the same workpiece feedrate, needs to calculate the distances between the preset and previous points for velocity calculations. The previous linear co-ordinates and rotary angles are then given to all the motors as the target position for retracing the die profile.

The workpiece retracing sub-routine is extracted from the Appendix C9 and is given at the end of this topic The distances between the present and earlier points for the top and bottom surface are calculated in line numbers 8290 - 8300. The difference between the present and previous angles is calculated in line number 8340 - 8350, Appendix **C9**.

All other calculations for velocity are carried out in the same way as described in topic 4.9.2.

At the end of each newly calculated reverse direction parameter command, the sub-routine sends them to the "OUTPUT DRIVER" (REFER STATEMENT 8710 - 8720, APPENDIX **C9**) initiates the motion in reverse direction in a synchronized way (Refer Statement 8880 - 8890, APPENDIX **C9**)

After retracing every single point the program checks the trigger input responses, if the workpiece is sufficiently retraced then the clear trigger input signal will be received by the "INPUT DRIVER" (REFER STATEMENT 8910).

Now the program asks for the new voltage levels and workpiece feedrate. The new velocity rates are then calculated in the same way as described in 4.9.2 for the rest of the points on die profile. The sub-routine then returns to the original place where the trigger input was initially activated (REFER STATEMENT 7290 -7300), and continues the machining process at new workpiece feedrate and voltage value in the cutting wire, for rest of the die to be machined.

```
8200 '-----------------------------------------------------------
8210 'THIS S-ROUTINE RETRACES W.P. TILL  Trg. INPUT IS CLEARED
8220 '-----------------------------------------------------------
8280 FOR Z = (L-1) TO 1 STEP -1
8290 RB(Z) = SQR(((XB(Z)-XB(Z-1))^2) + ((YB(Z)-YB(Z-1))^2))
8300 RT(Z) = SQR(((XT(Z)-XT(Z-1))^2) + ((YT(Z)-YT(Z-1))^2))
8310 AREA(Z) = ( (RB(Z)+RT(Z))*ZT )/2
8320 XA(Z) = XB1(Z) - XB1(Z-1)
8330 YA(Z) = YB1(Z) - YB1(Z-1)
8340 ALFA(Z) = ALFA1(Z)-ALFA1(Z-1)
8350 BETA(Z) = BETA3(Z)-BETA3(Z-1)
8360 S = SQR(XA(Z)^2 + YA(Z)^2) : H = AREA(Z)/S
8370 TM(Z) = S / ( FR/(H*60) )
8380 MIN(Z) = INT(TM(Z)/60)
8390 SEC(Z) = (((TM(Z)/60)-MIN(Z))*60)
8400 RTO = ABS(YA(Z) / XA(Z))
8410 VR = (FR/(H*60)) * (1/1.5)
8420 K = M1(Z-1) : B = 2
8430 IF K  < 0 THEN  B = 1
8440 D$ = MID$( STR$(K),B )
8450 S$ = MID$( STR$(1),1 )
8460 VX = SQR((VR^2) / (1+RTO^2))
8470 P = VX : GOSUB 9860 : VX$ = MID$(P$,1)
8480 CMD$(1,Z) = S$+"VS"+VX$+S$+"V"+VX$+S$+"D"+D$+S$+"I"
8490 K = M2(Z-1) : B = 2
8500 IF K < 0 THEN  B = 1
8510 D$ = MID$( STR$(K),B )
```

```
8520 S$ = MID$( STR$(2),1 )
8530 VY = VX * RTO
8540 P = VY : GOSUB 9860 : VY$ = MID$(P$,1)
8550 CMD$(2,Z)=S$+"VS"+VY$+S$+"V"+VY$+S$+"D"+D$+S$+"TS"+S$+"I"
8560 K = M3(Z-1) : B = 2
8570 IF K < 0 THEN B = 1
8580 D$ = MID$( STR$(K),B )
8590 S$ = MID$( STR$(3),1 )
8600 VB = (ABS(BETA(Z))*18) / (2*PI*TM(Z))
8610 P = VB : GOSUB 9860 : VB$ = MID$(P$,1)
8620 CMD$(3,Z) = S$+"VS"+VB$+S$+"V"+VB$+S$+"D"+D$+S$+"I"
8630 K = M4(Z-1) : B = 2
8640 IF K < 0 THEN B = 1
8650 D$ = MID$( STR$(K),B )
8660 S$ = MID$( STR$(3),1 )
8670 VA = (ABS(ALFA(Z)*100))/(2*PI*TM(Z))
8680 P = VA : GOSUB 9860 : VA$ = MID$(P$,1)
8690 CMD$(4,Z) = S$+"VS"+VA$+S$+"V"+VA$+S$+"D"+D$+S$+"I"
8700 CND$=CMD$(1,Z)+CMD$(2,Z):CDN$=CMD$(3,Z)+CMD$(4,Z)
8710 ADDRESS% = ADDRESS2% : CMD$ = CMD$(4,Z)   : GOSUB 11390
8720 ADDRESS%=ADDRESS1% : CMD$=CMD$(1,Z)+CMD$(2,Z)+CMD$(3,Z)
8730 GOSUB 11390
8740 '------------------------------------------------
8750 TME$= STR$(MIN(Z))+" MINUTES AND "+MID$(STR$(SEC(Z)),1,6)
8760 LOCATE 13,20
8770 PRINT "TIME REQUIRED FOR POINT NO. ";Z;" IS TO BE"
8780 LOCATE 14,20
8790 PRINT "RETRACED =";TME$;" SECONDS."
8800 LOCATE 18,13
8810 PRINT"COMMANDS SENT PC23 INDEXERS FOR POINT NO.";Z;"ARE="
8820 LOCATE 20,10
8830 PRINT "
8840 LOCATE 21,10
8850 PRINT "
8860 GOSUB 8150
8870 LOCATE 20,10:PRINT ;CND$:LOCATE 21,10:PRINT ;CDN$
8880 ADDRESS% = ADDRESS2% : CMD$ = "3G" : GOSUB 11390
8890 ADDRESS% = ADDRESS1% : CMD$ = "G123":GOSUB 11390
8900 GOSUB 11680
8910 IF ANSWER$ = "2:000000" + CHR$(13) THEN 8940
8920 IF Z = 1 THEN 8940
8930 NEXT Z
```

4.12. GEOMETRY DESCRIPTION AND MANUFACTURING OF SPUR GEAR

This software describes the geometry for a spur gear which has been developed based on Unwin's approximate construction method (98). The software developed is given in Appendix C10. This software is also divided into two parts. The first part of this software establishes the

spur gear terminology, x and y - coordinates and draws the same on the screen. The second part of this software, which starts at line number 3700, plans the path for the gear generation, sets machining conditions and controls the motion of x and y linear axes in the same manner as described for 3-D die generation. The operating mode of the indexer for the spur gear generation used is incremental (MPI).

1.	MODULE	6
2.	PITCH CIRCLE DIAMETER	72
3.	BASE CIRCLE DIAMETER	67.65788
4.	OUTSIDE DIAMETER (ADDENDUM DIAMETER)	84
5.	ROOT DIAMETER (DEDENDUM DIAMETER)	57
6.	CIRCULAR PITCH	18.84956
7.	NUMBER OF TEETH	12
8.	PRESSURE ANGLE IN DEGREES	20
9.	ADDENDUM	6
10.	DEDENDUM	7.5
11.	WIDTH OF TOP LAND (MINIMUM)	1.5
12.	WHOLE DEPTH OF TEETH	13.5
13.	WORKING DEPTH OF TEETH	12
14.	CLEARANCE	1.5
15.	FILLET RADIUS OF BASIC RACK OF TEETH	1.8
16.	TOOTH THICKNESS AT PITCH CIRCLE	9.424778
17.	SPACE WIDTH AT PITCH CIRCLE	9.424778
18.	TOOTH FLANK RADIUS	14.96681

TABLE 6 SHOWS A TYPICAL PRINTOUT OF THE TERMINOLOGY OF A SPUR GEAR.

The software developed for the spur gear needs only to know the module (M), the pitch circle diameter (PD) and the pressure angle (PA) of the spur gear. All other gear terminalogies are then calculated by using well known equations (REFER STATEMENTS 670-990 APPENDIX C10). The print out of all the terminologies then can be obtained. A

typical print out of a spur gear having module, pitch circle diameter and pressure angle of 6, 72 and 20 respectively is shown in **table 6**.

The further geometrical construction is carried out by referring to **figure 69** Firstly, from the computer generated spur gear terminology addendum circle, a dedendum circle, a pitch circle and base circle are drawn. Then from geometry of the spur gear, a point 'A' and a point 'C' are located on the base circle and addendum circle respectively. A point 'B' is then located at 1/3 length of the distance CA Then a tangential line BE is formed, on the base circle such that the angle OEB can be a right angle. The time BD is located at 3/4 of the BE. The point D is then treated as the centre of the tooth arc passing through B (REFER STATEMENTS 940-990). After having this information all the spur gear geometry can be described by using trigonometric functions

If the lengths of all three sides of a triangle are known, then by referring to **figure 70**, the angles B1, B2, B3 and B5 can be calculated by using cosine rule as

$$a^2 = b^2 + c^2 - 2\ bc\ \text{Cos}\ \beta_{(1,2\ \text{or}\ 3)}$$

Therefore, from the above equation

$$B_{(1,2\ \text{or}\ 3)} = \text{Cos}^{-1}\ \frac{(b^2\ +\ c^2\ -\ a^2)}{2bc}$$

and

$$B_5 = \cos^{-1} \frac{(a^2 + b^2 - c^2)}{2ab}$$

From, **figure 70**, the sides B and C for all three triangles $B_{(1,2,3)}$ remain the same, the length of side A changes. For angles B_3 and B_5 the lengths of all three sies remains the same.

By keeping the corresponding values of the sides A, B, and C of the triangles, the following expressions can be obtained.

$$\mathbf{B_1} = \cos^{-1} \frac{(\, OD^2 + CD^2 - (.5 * AC)^2 \,)}{2 * OD * CD}$$

$$\mathbf{B2} = \cos^{-1} \frac{(\, OD^2 + CD^2 - (.5 * DC)^2 \,)}{2 * OD * CD}$$

$$\mathbf{B_3} = \cos^{-1} \frac{(\, OD^2 + CD^2 - (.5 * PD)^2 \,)}{2 * OD * CD}$$

$$\mathbf{B_5} = \cos^{-1} \frac{(\, (.5 * PD)^2 + OD^2 - CD^2 \,)}{2 * (.5 * PD) * OD}$$

Where

CD = Radius of tooth arc   (REFER STATEMENT 980)

OD = Distance between centre of the tooth arc and centre of the spur gear (REFER STATEMENT 990)

DC = Dedendum circle diameter   (REFER STATEMENT 900)

PD = Pitch circle diameter

AC = Addendum circle diameter   (REFER STATEMENT 820)

The angle $Q_3 = B_1 - B_2$

(REFER STATEMETNS 1430-1510 APPENDIX C10)

The variable A1, A2, A3 and A5 are again used to calculate the angles B_1, B_2, B_3 and B_5 for the compatability of Cos^{-1} function using GWBASIC programming language

According to manipulators cartesian co-ordinate system, the open end of both the manipulator frames is from the side of III and IV quadrants (See figure 31a). For geometrical description and manufacturing the spur gear, the machining should start from the edge of the spur gear, rather than from the centre. Therefore the calculations for locating the initial point are started from the side of III and IV quadrants at 270°.

For full description of the spur gear geometry; firstly, the centre co-ordinates for both the curves of gear teeth are calculated by keeping the first arc centre of one side of the tooth arc (arc A) at 270° (REFER STATEMENT 1690 APPENDIX C10)

XOD(I) = OD * Cos (SY)   (REFER STATEMENT 1720)

YOD(I) = OD * Sin (SY   (REFER STATEMENT 1730)

Where XOD and YOD are the co-ordinates of all the centres of one side of the tooth curves (A arcs).

The centre co-ordinates of other side (B arcs) of the corresponding teeth are calculated by using the following equations.

$$XOE(I) = OD * Cos (SY) \qquad \text{(REFER STATEMENT 1860)}$$
$$YOE(I) = OD * Sin (SY) \qquad \text{(REFER STATEMENT 1870)}$$

Where DSY is the absolute angle between the two centres of the B arcs and T is the number of teeth of the spur gear (REFER STATEMENT 1830).

The location of the first centre of B arc with respect to the first centre of A arc from the geometry of the spur gear is calculated by referring to figure 70 and statements 1780-1820. Where angle B_5 and B_5, are the equal angles The angle Q_5 is in the fourth quadrant and is calculated from the co-ordinates XPD and YPD of a common point on the pitch circle and the arc B by using the following equation.

$$Q_5 = 2* + tan^{-1} \left(\frac{YPD}{XPD}\right) \qquad \text{(REFER STATEMENT 1810)}$$

The co-ordinates XPD and YPD on the pitch circle are calculated by using the angle PP (REFER STATEMENTS 1780-1800), where the angle PP is given by:

$$PP = [B_5 + PSY (1)] - (\pi /T)$$

(REFER STATEMENT 1780, APPENDIX C10)

Where angle (π/T) is equal to the tooth thickness at pitch circle (Refer figure 70).

After knowing all the centres and angles for teeth arcs of the spur gear, the calculations for user selected number of points on each tooth curve are carried out in sequential manner

Firstly the co-ordinates of arc A of the first tooth, secondly the co-ordinates of the arc B of the second tooth, and thirdly the co-ordinates of the arc A of the second tooth and so on. These calculations are extracted from Appendix C10 and are given below, where XCW and YCW are the co-ordinates of A curves and XDW and YDW are the co-ordinates of B arcs.

```
1900 '_____
1910 '**FOLLOWING LINES CALCULATE N POINTS ON INVOLUTE CURVES
1920 '------------------------------------------------------
1930 DSY - Q3 / N
1940 FOR I = 1 TO T STEP 2
1950 SY = ( ( PI-B1) + PSY(I) ) - DSY
1960 FOR J = 1 TO N+1
1970 SY = SY + DSY
1980 XCW(I,J) = CD * COS(SY) + XOD(I)
1990 YCW(I,J) = CD * SIN(SY) + YOD(I)
2000 NEXT J
2010 NEXT I
2020 DSY = Q3 / N
2030 FOR I = 1 TO T STEP 2
2040 SY = ( (PI-(Q3+(PI-B1))) + PI + PSZ(I) )  - DSY
2050 FOR J = 1 TO N+1
2060 SY = SY + DSY
2070 XDW(I,J) = CD * COS(SY) + XOE(I)
2080 YDW(I,J) = CD * SIN(SY) + YOE(I)
2090 NEXT J
2100 NEXT I
2110 DSY = Q3/N
2120 FOR I = 2 TO T STEP 2
2130 SY = ( (PI-B1) + PSY(I) ) - DSY
2140 FOR J = 1 TO N+1
2150 SY = SY + DSY
2160 XCW(I,J) = CD * COS(SY) + XOD(I)
```

```
2170 YCW(I,J) = CD * SIN(SY) + YOD(I)
2180 NEXT J
2190 NEXT I
2200 DSY = Q3/N
2210 FOR I = 2 TO T STEP 2
2220 SY = ( (PI-(Q3+(PI-B1))) + PI + PSZ(I) ) - DSY
2230 FOR J = 1 TO N+1
2240 SY = SY + DSY
2250 XDW(I,J) = CD * COS(SY) + XOE(I)
2260 YDW(I,J) = CD * SIN(SY) + YOE(I)
2270 NEXT J
2280 NEXT I
```

The co-ordinates for three points of teeth arcs at addendum circle are calculated using the following equations.

$$XA = .5 * AC * \cos(SY) \qquad \text{(REFER STATEMENT 2560)}$$

$$YA = .5 * AC * \sin(SY) \qquad \text{(REFER STATEMENT 2570)}$$

Where DSY (REFER STATEMENT 2530 APPENDIX C10) is the absolute angle difference between the last point of the arc A (i.e. angle SY = 5) and the first point of the arc B (i.e. angle R) (REFER STATEMENTS 2590 - 2800) for each tooth at the dedendum circle.

The co-ordinates for four points at the root circle are calculated using the following equations

$$XD = .5 * DC * \cos(SY) \qquad \text{(REFER STATEMENT 2840)}$$

$$YD = .5 * dc * \sin(SY) \qquad \text{(REFER STATEMENT 2850)}$$

Where DSY (REFER STATEMENT 2810 APPENDIX C10) is the absolute angle difference between the last point of the arc **A** (i,e angle SY = S) and the first point of the arc **B** (i,e angle R) (REFER STATEMENT 2590-2800)for each tooth at the dedendum circle.

All these calculated co-ordinates are then organised in a systematic manner so that they can represent a spur gear in a loop which starts at line number 2930. The line number 2920, 3240 and 3250 are representing the initial and the final cutting wire positions with reference to the spur gear centre. After organising all these points representing the spur gear, the software draws the gear on the screen. A typical printout of the spur gear drawing for the terminology shown in table 6 , is given in **figure 71.**

All of these X and Y co-ordinates of the spur gear are then saved in a disk data file named "FILE DAT". The FILE is kept equal to the initial data in numbers feed-in for the spur gear at the start i.e. the value of module, pitch circle diameter and pressure angle, so that by looking at the displayed disk directory data in the file named FILE DAT is saved and can be recognised (REFER STATEMENTS 910, 920 and 3560-3640). After saving these X and Y co-ordinates in the disk file, another part of the program starts for path planning and motion control for machining the spur gear.

14.12.1. PATH PLANNING FOR THE SPUR GEAR GENERATION

The path planning for manufacturing 2-D shapes i.e. spur gear is referred to the transformation of the linear distances into the motor steps and to determine the machining area, machining time and motor motion parameters (velocities) with respect to the desired workpiece feed rate and PC23 operating mode.

As the PC23 operating mode was selected to be incremental (MPI), therefore the distance parameters transformed into motor steps are also incremental.

The linear distance transformed into motor steps for X and Y axes will therefore be equal to

M1(I)   =   XA(I)* (5000/1.5)   (REFER STATEMENT 3970)

M2(I)   =   YA(I)* (500/1.5)   (REFER STATEMENT 3980)

Where XA and YA is the linear distance differences in millimetres between two consecutive points on the spur gear profile, 5000 is the motor steps per revolution and 1.5 is the lead screw pitch.

The cutting area defined by the two continuous points on the spur gear will be equal to the resultant lines distance (R) of the X and Y anes (REFER

STATEMENT 3990 APPENDIX C9) multiplied by the workpiece thickness (ZT) (REFER STATEMENT 4590).

The machining time between these two points on the spur gear is calculated by the following equation.

$$TM(I) = \sqrt{XA(I)^2 + YA(I)^2} * \frac{(60*ZT)}{FR}$$

(REFER STATEMENT 4200 APPENDIX C10)

Where FR is user the selected workpiece feedrate in mm^2/minute.

For determining the instantaneous velocity rates for synchronizing the X and Y axes motions the linear interpolation principle is followed here as well (Refer Topic 4.9.2). The workpiece feed rate needs to be changed from mm^2/min to revolution per second, so that to match the velocity units acceptable for the PC23 indexer commands. Therefore, the workpiece feed rate (FT) in revolutions per second is calculated by using the following equation.

$$FT = \frac{FR}{ZT*60} * \frac{1}{1.5}$$

(REFER STATEMENT 4250 APPENDIX C10)

Where FR is the user selected workpiece feed rate, ZT is the workpiece thickness, and 1.5 is the lead screw pitch in millimetres.

The ratio between the X and Y axes linear distances is kept as:

RTO = YA/XA   (REFER STATEMENT 4240)

Therefore   VX = VY/RTO and VY = VX* RTO

Where RTO is the ratio between velocities along the X-axis and Y-axis, Vk is the constant velocity along the X-axis and VY is the constant velocity along the Y-axis.

Therefore, according to pythagoras theorem the workpiece feed rate is given by

$$FT = \sqrt{Vx^2 + Vy^2}$$

By substituting the expression of VY in the above equation, the velocity along X-axis is obtained,

$$VX = \sqrt{FT^2/(1 + RTO^2)}$$

(REFER STATEMENT 4300 APPENDIX C10)

The velocity along the Y-axis is then calculated by using the following expression

Vy = VX*RTO   (REFER STATEMENT 4370)

These velocity values are then assigned to the commands 'VS' and 'V' (REFER STATEMENTS 4320 AND 4390 APPENDIX C10).

After calculating the above data and constructing all the commands for the points on the spur gear profile, the program prints all the X and Y co-ordinates, the resultant (R) travel, machining area and machining time. The calculated data print out for the spur gear having eight points on each tooth curve is given in **table 12**.

The procedure for setting the machining conditions is the same as described in topic 4.10 for 3-D shape generation, except the indexer operating mode used in here is incremental and the motion execution command 'G12' is used instead of 'G123'. The function of command 'G12' is to initiate the motion for motor number one and two in a synchronized manner. The commands 'VS', 'V', 'I', 'TS' and 'O' are used in the same manner as described in topic 4.10.

4.12.2. MOTION CONTROL FOR THE SPUR GEAR GENERATION

Motion control for any shape to be machined needs firstly, to initialize the communication between the micro-computer and the PC23 indexer. The subroutines described in topic 4.11. for communication initialization for 3-D shapes are the same for 2-D

shape motion control. The difference in here is that communication is only with the indexer number one, which controls both the X and Y linear axex, sets programmable outputs and checks the trigger input responses. The subroutines for resetting, sending commands to and receiving responses from the PC23 indexer one are given in Appendix C10 at line numbers 7800, 8080 and 8370 respectively.

The motion control subroutine for the spur gear generation starts at line number 4840 Appendix C10. The sequence of tasks in this subroutine for sending commands, receiving responses from the PC23 indexer one is carried out in the same way as for the 3-D die generation described in topic 4.11.2. Using the data shown in the table 11, a spur gear was generated. The photograph of this spur gear is shown in **plate 6**. The trigger input response is being checked at line number 4880. If the trigger input is encountered, then for retracing workpiece motion on the spur gear profile, the program branches to line number 5550 (REFER STATEMENT 4890, APPENDIX C10).

The subroutine for retracing the motion for the spur gear profile is different then for the 3-D die generation. As the operating mode of PC23 indexer used here is incremental, therefore for retracing the workpiece movements the velocity values are kept the same for any point to be retraced.

The sign of distance parameters values in motor steps are changed i.e. 1D5000 is changed to 1D-5000 and 2D-720 is changed to 2D720. By changing the sign of value given to 'D' command, the direction of the motor motion will be changed. This changing of the sign is done by using LEN and MID$ functions of the GWBASIC Programming Language (REFER STATEMENTS 5670 AND 5750 APPENDIX C10). All other parameter commands, values and procedure remains same as detailed in topic 4.11.2 until manufacturing of the last point on the spur gear is completed.

4.13. FEATURES OF THE SOFTWARE DEVELOPED

All the software for different functions in this research work are developed in GWBASIC Programming Language The reason for using BASIC Language is firstly, it is an easy language to use and is of sufficient speed for this particular application. It was also possible to program the PC23 indexers in BASIC Language. The computer used is an IBM compatible PC with 20 MB hard disk and 640 RAM.

In the software design development, special care was taken for the maximum linear and angular machining facilities offered by the manipulator, if any of the linear or angular movement caused damage to the manipulator, workpiece or the cutting wire during calculations before machining started, the program displays the error message

and gives option to the user either to quit or to re-start from the beginning. It means that the optimum angular cutting facilities are tried to be acheived by the precision manipulator

All the software developed are branched from one main program named "SUPER.BAS". By running this program, a menu appears on the screen which gives the shape or other functional choice to the user. After choosing the desired shape to be described and generated or other functional software, this program branches to the selected program. After the completion of the desired task the selected program can again be branched back to this main program. The flow chart and this main program is given in appendix C8.

The software developed are user friendly and display all of the error messages and instructions for the user throughout the process of program execution. The flexibility of describing the shape, size and the ease with which the user can understand the software is the main priority.

The software for describing the geometry and generating the 2-D or 3-D shapes are subdivided into two parts. There are two main reasons for dividing these 3-D shape generating programs into two parts. Firstly, having large numbers of array variables and length of the program, which occupies a large memory allocation in the computer

and secondly, to make the software more compact by using another part program by all 3-D geometry descriptive program. The BASIC statement ERASE is also used in both the part programs, which eliminates the array variables after being used and are not required any more (e.g. REFER STATEMENTS 2640 AND 4440 APPENDIX C1). The same memory is again used by redimensioning the other array variables in use. By using ERASE statement the program execution speed was noticeably increased as well.

The first part for the 3-D shapes, describes the top, bottom and intermediate geometries and also draws them including showing the wire cutting path between the top and the bottom surfaces as described in geometry description sections. Maximum of four intermediate sections data can be calculated and drawn. The data calculations and drawings for more than four sections can also be achieved after obtaining the data for the first four intermediate sections. ﹨ Each 3-D shape is given a different project number At the end of the first part of each 3-D shape, the program saves the information of the shape i.e. stage number (STG), and number of points (N) in one disk file the X and Y co-ordinates of the top and bottom surfaces. All the 3-D shape geometry describing programs then are linked to another part program.

The other part of the program firstly, loads the data of the corresponding 3-D shape by knowing the project number (REFER STATEMENT 5050 - 5150 APPENDIX C9), then

plans the path for the 3-D shape, sets the machining conditions and controls the motor motion for each 3-D shape as described before. A simplified flow chart for 3-D shape generation is shown in **figure 58**. For selecting the voltage level in the cutting wire the program prints the menu and levels of the voltage value as shown below.

```
        PLEASE ! SELECT THE LOWEST VALUE TO CHECK
            RETRACING CAPABILITY OF THE SYSTEM.

    PREVIOUSLY VOLTAGE SUPPLIED TO THE WIRE WAS  6  VOLTS.
    NOW YOU CAN SELECT NEW VOLTAGE FROM FOLLOWING OPTIONS.
        ***************************************
        * VOLTAGE 1.......     .....1.25  VOLTS *
        * VOLTAGE 2.............. 6       VOLTS *
        * VOLTAGE 3...............5.5     VOLTS *
        * VOLTAGE 4...............5       VOLTS *
        * VOLTAGE 5...............6       VOLTS *
        ***************************************
        SELECT VOLTAGE BY PRESSING KEYS 1-5 KEY
```

During machining, the program points the total machining time, machining time for the segment being generated, time required for machining rest of the shape, total machining area, user selected workpiece feed rate and voltage in the cutting wire, and also the commands sent to PC23 indexers for the segment being manufactured. A typical print out is shown on the following page.

A number of other programs other than 2-D/3-D shape generation were also developed. One of the functional programs developed was to communicate with any of the Ks-drive through the RS-232 port. This program is given in Appendix B10. The functions of this program are to display, change and save the KS-drive servo parameters like, PID and V-gains, PID and V-gain maximum, average and peak

TOTAL MACHINING TIME FOR THIS DIE PROFILE IS = 11 MINUTES AND 30 21 SECONDS
REST OF THE PROFILE NEEDS MACHINING TIME OF = 9 MINUTES AND 46.07 SECONDS.
TIME FOR THIS SEGMENT TO BE MANUFACTURED IS = 0 MINUTES AND 11.35 SECONDS.
TOTAL MACHINING AREA OF THE DIE IS = 9202.037mm.Sqr
PRESENT WORKPIECE FEEDRATE IS = 000 mm. Sqr /min.
THE VOLTAGE IN THE CUTTING WIRE IS APRX. 6 VOLTS.

NOW POINT NUMBER 3 IS BEING MANUFACTURED.

PRESS 'R' IF WISH TO CHANGE VOLTAGE IN THE
CUTTING WIRE OR TO TEST RETRACING FACILITY

COMMANDS SENT TO THE PC23 INDEXERS FOR POINT 3 ARE

1VS.1143 1V.1143 1071656 1I 2VS.200 2V.200 2025672 2TS 21
3VS.0071 3V.0071 3D-2587 3I 3VS.0051 3V.0051 3D127 3I

allowable currents to the motor, slip fault dead band and

displays servo status flags Where proportional (P),

integral (I), derivative (D) and velocity (V) servo

parameters affect the responsiveness of the system, average

and peak currents affect the motor torque as described in

chapter three. This displayed parameter for motor one and

options on the screen are shown below.

```
••••• ••••••••••••••••• •••••••••••MAIN MENO•••••••••••••••••••••••••••••• ••• •
   THE VALUES OF THE P-I-D-V GAINS ARE GIVEN IN A %AGE OF A MAXIMUM TERM GAINS
              (GAIN VALUE = PERCENTAGE  X  MAXIMUM GAIN VALUE)
   •••••••• •COMMAND•••PRESENT SETTING OF THE TERMS•••••••••CODE TO PROCEED••••••
              1CPG *PROPORTIONAL_GAIN=35_PERCENT                1
              1CIG *INTEGRAL_GAIN=0_PERCENT                     2
              1CDG *DIFFERENTIAL_GAIN=4_PERCENT                 3
              1CVG *VELOCITY_GAIN=50_PERCENT                    4
              1CPM *PROPORTIONAL_GAIN_MAXIMUM=1000              5
              1CIM *INTEGRAL_GAIN_MAXIMUM=1280                  6
              1CDM *DIFFERENTIAL_GAIN_MAXIMUM=30                7
              1CVM *VELOCITY_GAIN_MAXIMUM=10000                 8
              1CMR *MOTOR_RESOLUTION=5000_STEPS/REV             9
              1CCA *AVERAGE_CURRENT_LIMIT=02 100_AMPERES        A
              1CCP *PEAK_CURRENT_LIMIT=08 000_AMPERES           P
              1CDB *SLIP_FAULT_DEADBAND=0 STEPS                 D
              1CPE *MAXIMUM_POSITION_ERROR=5000_STEPS           M
              1DFS *0000_0000_0000_0000_0000_0000_0000_0000*

••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••
   PLEASE' PRESS THE CODE NUMBER FOR CHANGING OR TESTING THESE TERM VALUES
       PRESS   R    TO RUN THE MOTOR WITH THESE VALUES  AND    E   TO EXIT
       PRESS   S    TO SAVE THESE VALUES          I  AM  WAITING      '
```

FIGURE 58
FLOW CHART OF THE
3-D DIE GENERATION

PART I

PART II
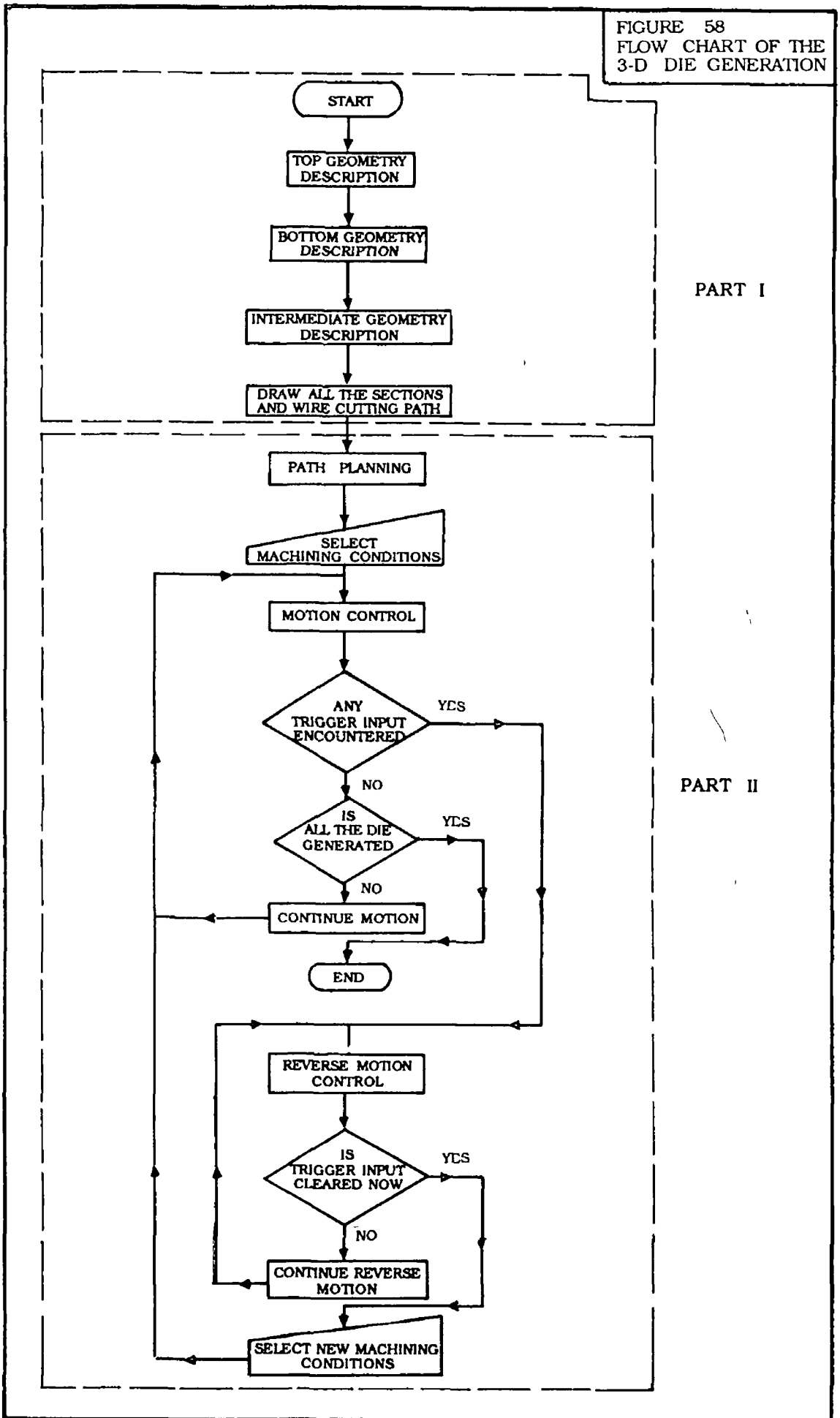
All of the above values can be changed through this program, the motor torque and responsiveness can also be checked by running the appropriate motor. If wished, the new values can be saved in the non-volatile EEPROM memory of the KS-drive. During transformation these servo parameters, if the user selected values are outside the range, the program then displays the corresponding message and gives the option to set the new values, again to the user. The present set values for all the four KS-drives are shown at the end of Appendix B10

Another functional software developed, is to change the voltage levels in the cutting wire. This program is given in Appendix C11. This program gives access to the user to select the new voltage in the cutting wire. Selecting new voltage in the cutting wire means to send programmable output signal to the PVR through the PC23 indexer   The PVR circuit is described in detail in chapter three. In total five new values can be achieved. If any value other than the five is desired, then that value must be set in the PVR circuit by calibrating the corresponding potentiometer.

The third functional software developed, is for manipulating the precision manipulator along the X and Y axes using the arrow keys and function keys. This software is given in Appendix C12.

As all the 3-D shapes are generated for starting

machining from the centre and the spur gear needs to be started from the edge, therefore the manipulator needs to be positioned at different places. If at some occasions during machining, the process is disturbed and stopped, the manipulator is needed to be brought at the initial position. This program allows to bring the manipulator at the same initial position.

4.14. TEST PROCEDURE

Before any test was carried out, the polystyrene pieces of 120 x 120 mm of different thicknesses (ZT) were cut from sheet blocks A small size hole was drilled centrally in all the workpieces so that the cutting wire could be passed through as an initial machining position.

The polystyrene used to carry out the tests was bought from Dow Chemical Company Limited which has the density of 34 Kg/m^3, compressive strength of 300 KN/m^2 and thermal conductivity of 2.5 x 10^{-2} W/mk.

For 3-D die generation, firstly the precision manipulator was brought to zero position of linear movement (middle of X and Y total linear travels). By using one of the functional software, then the rotary frames were kept in parallel position with reference to the main base plate of the manipulator (drawing No. 01D03). For spur gear generation, the y-axis was kept at the end of travel towards CCW direction, because of initial machining

position is at the edge of the work piece towards CW direction. After doing this the wire cutting unit was brought manually near to the frames so that the cutting wire could be kept at the centre of the frames i.e. junction point of the planes rotating around the X and Y axes.

Then, the wire arrangement, which is hooked onto the spring was opened and after passing this wire through the centrally drilled hole of the work piece, it was again fixed with the spring and the work piece was housed on the inner frame of the manipulator. The wire passing through the centre of the work piece is now at absolute zero position. This absolute position of the wire is already described in all 3-D software.

For spur gear manufacture the workpiece was firstly housed on the inner frame and the wire cutting unit was brought near to the workpiece so, that the cutting wire can be at the middle of the open edge of work piece. This initial wire position with reference to the centre of the workpiece was also pre-described in the software.

The tension in the wire was pre-checked, so that the cutting wire could maintain its vertical position. The micro-switch adjuster was then fixed in the closest proximity of the spring on the wire cutting unit, so that any smallest increase in the wire tension can cause the micro switch latter in closed position by the tension

spring   The cables supplying power to the cutting wire
were connected to the PVR circuit; the PVR circuit was then
linked to the PC23 indexer number one and with the
multimeter.

Having done this, the program was started.   The
program firstly prompts for a number of points, workpiece
thickness and magnification of the top and bottom surfaces
on the workpiece for the corresponding shape geometry. The
corresponding program developed, goes through calculations
to find out the X and Y co-ordinates, resultant distances,
angles the points make with absolute zero in cartesion
co-ordinate and sector areas for the top and bottom
surfaces as described previously.   The program then
calculates the same data for user selected number of
intermediate sections (maximum of four).   The data
calculated for the top, bottom and intermediate sections
can be displayed as well.   The reduction ratio of area at
the bottom and intermediate sections is also displayed. The
program then displays the drawings of the top, bottom and
intermediate sections in one screen. The drawings for each
of the surface are displayed separately showing the Z
co-ordinate value and the area enclosed by the profile.

The program then branches to another part program
which calculates the alpha and beta angles made by two
corresponding points at the top and bottom surfaces and
checks each of the angles whether it is achievable or not.
If the angular movement causes any damage to

manipulator/workpiece/cutting wire then the program displays the corresponding error message and asks the user either to quit or to restart the program again for new values to be fed in. The program also compensates the backlesh of 1° (250 metre steps) in motor 3 for beta motion. The computer then prompts for the workpiece feed rate which the user wants. After inputting this workpiece feed rate the program calculates the machining time and velocity rates given to the appropriate axes. The calculated data alpha, beta, machining time and machined area at user selected workpiece feed rate for each point are then displayed on the screen as described in topic 4.9 2.

After these calculations are completed the power is supplied to the PC23 indexer adapter boxes, PVR circuit, multimeter and corresponding KS-drives followed by the software messages. The voltage selection was carried out from the table shown in topic 4.13 displayed by the software as well.

The generation of the 3-D die cavity/spur gear is started automatically for each point at user selected workpiece feedrate and voltage. During the die generation the program displayed the total machining time, the machining time for the current segment being manufactured, time required for the rest of the die to be manufactured,

total machining area, workpiece feedrate, voltage supplied
to the cutting wire and commands sent to the indexer.
Sample screen printout is also shown in topic 4.13.

At any stage, during the die generation, if "R" is
pressed through the keyboard, then the process will stop
and the voltage selection menu will appear on the screen.
By selecting a lower voltage value, the die generation
process will continue from the point the "R" key was
pressed at the new selected voltage supply rate and the
same workpiece feedrate. Now, if this new voltage rate is
unable to machine the workpiece, then the tension at the
cutting wire will increase, which will cause a pull on the
spring. As the spring starts to pull, the lever of the
micro-switch which is in touch with the spring also starts
to close. As soon as the micro-switch closes the trigger
signal is read by the computer program. By the activation
of this signal the program branches to another subroutine.
This subroutine firstly stops all the motors and also cuts
off the power supply to the cutting wire. Then the reverse
motion of all the motors starts for each point. This
reverse motion releases the tension on the cutting wire and
brings it to the original vertical position. As the wire
becomes vertical the micro-switch opens and the cleared
signal is then read by the computer program. Now the
program prompts for new workpiece feedrate and voltage in
the cutting wire. The new machining time and velocities
for each point from the retraced point are calculated and

displayed. The program then returns back to the original subroutine to generate the rest of the die profile at the new workpiece feedrate and voltage levels.

4.15. PROBLEMS ENCOUNTERED DURING SOFTWARE DEVELOPMENT

One of the main problems encountered was due to the large number of array variables and size of the programme. Each of the 2-D and 3-D shape – generating software was divided into two parts and within each part the BASIC statement ERASE was used to eliminate used variables, which were not required anymore.   Then the available memory was utilized for dimensioning new array variables.

The last part of the program which controls the motor motion needs the commands sent to the PC23 indexers in string variables. The larger the number of points on the profile, the greater the string memory required, which reduces the speed of program execution.

The other major problems encountered were related to the unexpected responses of the PC23 indexer commands, which were not mentioned anywhere in the literature supplied by the vendor. In the first sight these commands seemed to be straight forward. However, in implementing these it was found that the responsiveness was different from what it should be. In order to obtain the expected

responses and avoid damage to the mechanical parts of the manipulator, substantial effort had to be spent to rectify the situation.

If the values for velocity and acceleration were needed to be less than one revolution second and one revolution per second square respectively, but these values were calculated by the computer in 1st or 2nd order precision format (exponential form) then the indexer took these values as whole numbers ignoring the instruction format for fractional numbers. For avoiding the above case, a separate subroutine was developed, which changes the computer format of 1st/2nd order precision into simple decimal format (REFER STATEMENTS 9860 - 9960 APPENDIX C9).

By issuing synchronized motion execution command "G123", all the three motors should start motion at the same time, and if the acceleration, velocity and distance rates are the same, then all three motors should stop at the same time as well. When this command was issued, it was seen that one of the three motors randomly kept continuously moving until the power was cut off. This problem was solved by continuously monitoring all the three motor motions until they have completed the commanded distance to be travelled. As soon as the commanded distance was travelled the commands for all three motors were issued to stop. This subroutine is extracted from the Appendix C9 and is given below.

```
8110 '_____
8120 '** FOLLOWING LINES   CHECK THAT, IS THE   COMMANDED MOVE
8130 '** COMPLETED OR NOT. IF YES, THEN STOP ALL   THE MOTORS
8140 '-----------------------------------------------------
8150 ADDRESS% = ADDRESS1%
8160 CH = INP(ADDRESS%+1)
8170 IF (CH AND 1)+(CH AND 2)+(CH AND 4)=7 THEN 8180 ELSE 8160
8180 CMD$ = "1S 2S 3S" : GOSUB 11390
8190 RETURN
```

The command "VS" was described in the literature supplied, if it is issued only once then all the following moves will have the same initial instantaneous velocities When the process was tried to obtain different instantaneous velocities for each segment to be generated according to constant workpiece feedrate, all the motors were observed to have the same initial instantaneous velocities for all the points. In this particular application where the workpiece feedrate is user selected and the linear and angular distances are not the same between two corresponding points, it was very difficult to achieve different instantaneous velocities for each segment to be generated.

It is of basic importance in WEDM process to have constant workpiece feedrate with respect to other machining conditions. A number of different combinations of PC23 indexer commands were tried, but none of the response seemed to be satisfactory. When the command "V" was added followed by "VS" command, the instantaneous velocities were observed to be changing for all different points and the response was very satisfactory (REFER

STATEMENTS 6500, 6580, 6660 and 6740 APPENDIX C9). This combination of "VS" and "V" commands was also not mentioned in the literature supplied.

The response of the command "O" for sending programmable output was also very confusing. Before any motion execution starts, the PC23 indexer operating mode (absolute/incremental) and the motors resolution (ie 5000 steps/revolutions) were set. Then the voltage in the cutting wire was selected through the PVR circuit by using "O" command. Following this, the motor motions were initiated in sequence for all the points on the die profile. The system response was found to be very satisfactory upto this stage. As soon as, the attempt was made to change the voltage level in the cutting wire or any trigger input was encountered during the shape generating process, it was observed that the motor resolutions were changed, (25000 steps/revolution, as standard), ie. the speeds for motor 1, 2 and 3 on indexer number one, were significantly increased. Whereas motor 4 was observed to be moving according to the commanded speed. As it has been described in chapter three, the distance and velocity are motor resolution dependent and the KS-drives are set at 5000 steps/revolution. Therefore any increase of motor resolution on PC23 indexer caused higher frequency ranges sent to the KS-drive, which caused the increased motor speeds.

It was also described earlier that the connections of

the PVR circuit are with indexer one, which controls the first three motors (for X and Y linear axes and one for rotary motion beta) as well. Besides changing the motor resolution, the commanded voltage change throughout the PVR circuit by command "O" was not satisfactorily working. Sometimes the new voltage value was observed to be changing after some delay and sometimes it did not change at all. Therefore, it was obviously the function of the programmable output command "O". This unexpected response of the command "O" was not explained anywhere in the literature supplied and this caused a great deal of confusion.

A number of possible combinations of commands were tried to rectify the situation to get the desired response without changing the motor resolution. In the end, the system response was found stable by an addition of commands "MR" and MPI" or "MPA" with "O" command. Therefore the variable CPD$ was combined with the commands "O" throughout the control software. Where CPD$ = "IMR6 2MR6 3MR6 1MPA 2MPA 3MPA" for 3-D shape generation, (REFER STATEMENTS 8230, 10080, 10090 AND 10430 - 10470 APPENDIX C9). The CPD$ = "1MR6 2MR6 1MP1 2MP1 for the spur gear generation. (REFER STATEMENTS 5550, 6850, 6860 AND 7190 - 7230 APPENDIX C10).

TABLE 7

Shows the computer generated data for circle shape at the top surface.

*** CALCULATIONS FOR TOP SUREACE (CIRCLE) STARTS HERE ***
****

Serial Number	XT (mm)	YT (mm)	RADIUS (mm)	THETA (Degrees)	SECTOR AREA (mm Sq)	TOTAL AREA (mm Sq)
1	25	0	25	0	0	0
2	24 786	3 263	25	7 5	40 906	40 906
3	24 148	6 47	25	15	40 906	81 812
4	23 096	9 567001	25	22 5	40 906	122 71
5	21 65	12 5	25	29 999	40 906	163 62
6	19 833	15 219	25	37 499	40 906	204 53
7	17 677	17 677	25	44 999	40 906	245 43
8	15 219	19 833	25	52 499	40 906	286 34
9	12 5	21 65	25	60	40 906	327 24
10	9 567001	23 096	25	67 499	40 906	368 15
11	6 47	24 148	25	74 999	40 906	409 06
12	3 263	24 786	25	82 499	40 906	449 96
13	0	25	25	89 999	40 906	490 87
14	-3 263	24 786	25	97 499	40 906	531 77
15	-6 47	24 148	25	104 99	40 906	572 68
16	-9 567001	23 096	25	112 49	40 906	613 59
17	-12 5	21 65	25	120	40 906	654 49
18	-12 875	21 429	25	120 99	5 454	659 95
19	-13 247	21 201	25	121 99	5 454	665 4
20	-13 615	20 966	25	122 99	5 454	670 86
21	-13 979	20 725	25	123 99	5 454	676 31
22	-14 339	20 478	25	124 99	5 454	681 76
23	-14 694	20 225	25	125 99	5 454	687 22
24	-15 045	19 965	25	126 99	5 454	692 67
25	-15 391	19 7	25	127 99	5 454	698 13
26	-15 732	19 428	25	128 99	5 454	703 58
27	-16 069	19 151	25	129 99	5 454	709 03
28	-16 401	18 867	25	130 99	5 454	714 49
29	-16 728	18 578	25	131 99	5 454	719 94
30	-17 049	18 283	25	132 99	5 454	725 4
31	-17 366	17 983	25	133 99	5 454	730 85
32	-17 677	17 677	25	134 99	5 454	736 31
33	-17 983	17 366	25	135 99	5 454	741 76
34	-18 283	17 049	25	136 99	5 454	747 21
35	-18 578	16 728	25	137 99	5 454	752 67
36	-18 867	16 401	25	138 99	5 454	758 12
37	-19 151	16 069	25	139 99	5 454	763 58
38	-21 084	13 432	25	147 49	40 906	804 48
39	-22 657	10 565	25	154 99	40 906	845 39
40	-23 842	7 517	25	162 49	40 906	886 29
41	-24 62	4 341	25	169 99	40 906	927 2
42	-24 976	1 09	25	177 49	40 906	968 11
43	-24 904	-2 178	25	184 99	40 906	1009
44	-24 407	-5 41	25	192 49	40 906	1049 9
45	-23 492	-8 55	25	199 99	40 906	1090 8

46	-22 175	-11 543	25	207 49	40 906	1131 7
47	-20 478	-14 339	25	214 99	40 906	1172 6
48	-18 431	-16 889	25	222 49	40 906	1213 5
49	-16 069	-19 151	25	229 99	40 906	1254 4
50	-13 432	-21 084	25	237 49	40 906	1295 3
51	-10 565	-22 657	25	244 99	40 906	1336 2
52	-7 517	-23 842	25	252 5	40 906	1377 1
53	-4 341	-24 62	25	260	40 906	1418
54	-3 623	-24 736	25	261 66	9 09	1427 1
55	-2 902	-24 83	24 999	263 33	9 09	1436 2
56	-2 178	-24 904	24 999	265	9 09	1445 3
57	-1 453	-24 957	25	266 66	9 09	1454 4
58	- 727	-24 989	25	268 33	9 09	1463 5
59	0	-25	25	270	9 09	1472 6
60	727	-24 989	25	271 66	9 09	1481 7
61	1 453	-24 957	25	273 33	9 09	1490 8
62	2 178	-24 904	25	275	9 09	1499 8
63	2 902	-24 83	25	276 66	9 09	1508 9
64	3 623	-24 736	25	278 33	9 09	1518
65	4 341	-24 62	25	279 99	9 089	1527 1
66	6 47	-24 148	25	284 99	27 27	1554 4
67	8 55	-23 492	25	289 99	27 27	1581 7
68	10 565	-22 657	25	295	27 27	1608 9
69	12 499	-21 65	25	299 99	27 27	1636 2
70	14 339	-20 478	25	304 99	27 27	1663 5
71	16 069	-19 151	25	309 99	27 27	1690 7
72	17 677	-17 677	25	314 99	27 27	1718
73	19 151	-16 069	25	319 99	27 27	1745 3
74	20 478	-14 339	25	324 99	27 27	1772 5
75	21 65	-12 5	25	329 99	27 27	1799 8
76	22 657	-10 565	25	334 99	27 27	1827 1
77	23 492	-8 55	25	339 99	27 27	1854 4
78	24 148	-6 47	25	344 99	27 27	1881 6
79	24 62	-4 341	25	349 99	27 27	1908 9
80	24 904	-2 178	25	354 99	27 27	1936 2
81	25	0	25	359 99	27 27	1963 4

TOTAL AREA OF THE TOP SURFACE (CIRCLE AT Z = 39 mm) = 1963 495 mm Square

TABLE 8

Shows the computer generated data for complex shape at the bottom surface.

CALCULATIONS FOR BOTTOM SUREACE (COMPLEX) STARTS HERE
****

Serial Number	XB (mm)	YB (mm)	RESULTANT (mm)	THETA (Degrees)	SECTOR AREA (mm Sq)	TOTAL AREA (mm Sq)
1	20	0	20	0	0	0
2	19 04	3 202	19 654	9 548001	32 185	32 185
3	17 483	6 161	18 922	19 413	30 826	63 012
4	15 387	8 766	18 123	29 669	29 399	92 411
5	12 83	10 92	17 279	40 4	27 959	120 37
6	10 916	12 064	16 559	47 861	17 854	138 22
7	8 87	12 954	15 985	55 599	17 253	155 47
8	6 726	13 573	15 424	63 636	16 687	172 16
9	4 521	13 911	14 888	71 993	16 165	188 33
10	2 988	14 159	14 549	78 08	11 244	199 57
11	1 476	13 804	14 177	83 893	10 196	209 77
12	213	12 902	13 393	89 053	8 077	217 85
13	- 612	11 586	12 253	93 025	5 204	223 05
14	- 854	10 576	11 107	94 621	1 717	224 77
15	- 829	9 537	10 092	94 97	31	225 08
16	- 538	8 54	9 064901	93 60299	- 979	224 1
17	0	7 652	8 104	90	-2 066	222 03
18	394	7 066	7 364	86 802	-1 513	220 52
19	629	6 4	6 754	84 385	- 962	219 56
20	688	5 697	6 085	83 111	- 411	219 15
21	568	5 001	5 386	83 52	103	219 25
22	276	4 359	4 7	86 372	55	219 8
23	- 168	3 81	4 091	92 525	898	220 7
24	- 736	3 391	3 642	102 24	1 125	221 82
25	-1 392	3 13	3 448	113 97	1 216	223 04
26	-2 208	3 273	3 687	124 01	1 19	224 23
27	-3 007	3 496	4 28	130 69	1 069	225 3
28	-3 78	3 798	4 985	134 86	904	226 21
29	-4 52	4 173	5 755	137 27	696	226 9
30	-6 349	5 19	7 176	140 73	1 552	228 46
31	-8 025	6 444	9 246	141 23	376	228 83
32	-9 517901	7 911	11 334	140 26	-1 088	227 74
33	-10 8	9 566	13 402	138 46	-2 821	224 92
34	-12 042	10 097	15 071	140 02	3 079	228
35	-13 378	10 308	16 302	142 38	5 479	233 48
36	-14 724	10 186	17 397	145 32	7 768	241 25
37	-16	9 737001	18 317	148 67	9 807901	251 06
38	-17 861	7 741	19 098	156 56	25 123	276 18
39	-19 193	5 359	19 697	164 39	26 518	302 7
40	-19 92	2 728	20 017	172 2	27 281	329 98
41	-20	0	20 053	180	27 368	357 35
42	-20 022	-2 431	20 084	186 92	24 373	381 72
43	-19 685	-4 839	20 22	193 81	24 576	406 3
44	-18 995	-7 17	20 287	200 68	24 677	430 98
45	-17 968	-9 373901	20 285	207 55	24 673	455 65
46	-17 335	-10 413	20 244	210 99	12 308	467 96
47	-16 626	-11 402	20 191	214 44	12 268	480 23
48	-15 846	-12 336	20 121	217 9	12 216	492 44
49	-15	-13 21	20 035	221 36	12 151	504 6
50	-14 137	-14 29	20 044	225 3	13 811	518 41

51	-13 049	-15 143	20 046	229 24	13 815	532 22
52	-11 794	-15 723	19 823	233 12	13 298	545 52
53	-10 439	-16	19 38	236 87	12 289	557 81
54	-9 107001	-15 735	18 642	239 93	9 286	567 1
55	-7 977	-14 98	17 576	241 96	5 461	572 56
56	-7 222	-13 852	16 297	242 46	1 157	573 72
57	-6 955	-12 519	14 972	240 94	-2 971	570 75
58	-6 724	-11 05	13 629	238 67	-3 676	567 07
59	-6 647	-9 563	12 291	235 19	-4 584	562 49
60	-6 724	-8 077	11 079	230 22	-5 329	557 16
61	-6 956	-6 608	10 052	223 53	-5 901	551 25
62	-5 732	-5 675	8 83	224 71	805	552 06
63	-4 246	-5 282	7 422	231 2	3 121	555 18
64	-2 721	-5 487	6 451	243 61	4 507	559 69
65	-1 392	-6 259	6 269	257 46	4 748	564 44
66	- 775	-7 069	6 762	263 73	2 504	566 94
67	- 22	-7 922	7 518	268 4	2 303	569 24
68	271	-8 813	8 371	271 76	2 051	571 3
69	696	-9 738	9 29	274 08	1 752	573 05
70	2 289	-11 402	10 696	281 35	7 255	580 3
71	4 128	-12 791	12 535	287 88	8 958901	589 26
72	6 165	-13 868	14 309	293 96	10 861	600 13
73	8 347	-14 608	16 001	299 74	12 912	613 04
74	10 699	-14 832	17 556	305 8	16 296	629 33
75	13 01	-14 345	18 827	312 2	19 8	649 13
76	15 071	-13 192	19 698	318 8	22 341	671 48
77	16 696	-11 477	20 145	325 49	23 69	695 17
78	18 165	-8 829001	20 229	334 07	30 659	725 83
79	19 22	-5 99	20 165	342 69	30 562	756 39
80	19 836	-3 024	20 099	351 33	30 462	786 85
81	20	0	20 033	360	30 361	817 21

TOTAL AREA OF THE BOTTOM SURFACE (COMPLEX AT Z=0) = 817 2175 mm Square

REDUCTION RATIO AT THE BOTTOM SURFACE AREA = 58 37781 %

TABLE 9

Shows the computer generated data for crescent shape   at the bottom surface.

CALCULATIONS   FOR BOTTOM SUREACE (CRESCENT) STARTS HERE
****

Serial Number	XB (mm)	YB (mm)	RESULTANT (mm)	THETA (Degrees)	SECTOR AREA (mm Sq)	TOTA_ AREA (mm S:
1	15	0	15	0	0	0
2	14 841	2 173	15	8 333	16 362	16 36_
3	14 369	4 302	15	16 6b6	16 362	32 7_4
4	13 594	6 339	15	25	16 362	49 0_7
5	12 532	8 242	15	33 333	16 362	65 4+9
6	11 205	9 971	15	41 666	1b 362	8_ 8_2
7	9 641	11 49	15	50	16 362	98 174_.
8	7 874	12 766	15	58 333	16 362	114 53
9	5 941	13 773	15	66 66b	16 362	130 89
10	3 882	14 488	15	75	16 362	147 2b
11	1 741	14 898	15	83 333	16 362	163 62
12	- 43b	14 993	15	91 666	16 362	179 98
13	-2 604	14 772	15	100	1b 362	19b 34
14	-4 718	14 238	15	108 33	16 362	212 7_
15	-6 731	13 404	15	116 66	16 362	229 07
16	-8 602899	12 287	15	125	16 362	245 43
17	-10 293	10 91	15	133 33	16 362	261 ⁻9
18	-11 766	9 303001	15	141 66	16 362	278 16
19	-12 99	7 499	15	150	16 362	294 52
20	-13 94	5 538	15	158 33	16 362	310 88
21	-14 595	3 459	15	166 66	16 362	327 24
22	-14 942	1 307	15	175	16 362	343 61
23	-14 974	- 872	15	183 33	16 362	359 97
24	-14 69	-3 033	14 999	191 66	16 362	376 33
25	-14 095	-5 13	15	200	16 362	392 69
26	-13 203	-7 119	15	208 33	16 362	40⁹ 06
27	-12 031	-8 957	15	216 66	16 362	425 +2
28	-10 606	-10 606	15	225	16 362	441 78
29	-8 957	-12 031	15	233 33	16 362	458 14
30	-7 118	-13 203	15	241 66	1b 362	474 51
31	-5 13	-14 095	15	250	16 362	490 87
32	-6 409	-13 046	14 7b7	243 83	-11 733	47⁹ 14
33	-7 545	-11 843	14 289	237 49	-11 291	467 8+
34	-8 520001	-10 506	13 785	230 96	-10 841	45⁷
35	-9 316	-9 056	13 26	224 18	-10 391	44b _1
36	-9 923001	-7 517	12 721	217 14	-9 946	43_ _
37	-10 329	-5 913	12 176	209 78	-9 516	427 _5
38	-10 529	-4 271	11 632	202 07	-9 104901	418 _4
39	-10 519	-2 616	11 10_	193 96	-8 722	409 32
40	-10 299	- 976	10 59_	185 41	-8 372	40_ _5
41	-9 873	621	10 119	176 39	-8 061	392 88
42	-9 248	2 153	9 694	166 89	-7 794	385 _+
43	-8 432901	3 593	9 331001	156 92	-7 576	377 5_
44	-7 442	4 918	9 043899	146 54	-7 409	370 _
45	-6 291	6 107	8 844	_35 85	-7 296	362 8_
46	-4 999	7 14	8 741901	124 99	-7 239	355 5⁻
47	-3 586	8 001001	8 741901	114 14	-7 239	34_ _3
48	-2 076	8 675901	8 844	103 45	-7 296	34_ 03
49	- 492	9 153	9 043899	93 078	-7 409	333 _2
50	1 139	9 425901	9 331001	83 107	-7 576	326 _5

51	2 792	9 49	9 694	73 602	-7 794	318 25
52	4 44	9 344	10 119	64 581	-8 061	310 19
53	6 056	8 99	10 592	56 031	-8 372	301 82
54	7 614	8 432901	11 101	47 92	-8 722	293 1
55	9 089	7 684	11 632	40 21	-9 104901	283 99
56	10 458	6 753	12 176	32 855	-9 516	274 47
57	11 697	5 657	12 721	25 811	-9 946	264 53
58	12 786	4 412	13 26	19 039	-10 391	254 14
59	13 71	3 039	13 785	12 501	-10 841	243 29
60	14 451	1 561	14 289	6 164	-11 291	232
61	15	0	14 767	359 99	-11 291	220 71

TOTAL AREA OF THE BOTTOM SURFACE (CRESCENT AT Z=0) = 220 7149 mm Square

REDUCTION RATIO AT THE BOTTOM SURFACE AREA = 82 43595 %

TABLE 10

Shows the computer generated data for the intermediate section of the circle to complex shape at Z coordinate of 10 mm.

CALCULATIONS FOR INTERMEDIATE SURFACE 1 STARTS HERE
****

Serial Number	X 1 (mm)	Y 1 (mm)	RESULTANT (mm)	THETA (Degrees)	SECTOR AREA (mm Sq)	TOTAL AREA (mm Sq)
1	21 282	0	21 282	0	0	0
2	20 513	3 218	21 023	8 915	34 388	34 386
3	19 192	6 24	20 473	18 012	33 273	67 662
4	17 364	8 971	19 863	27 323	32 059	99 722
5	15 092	11 325	19 207	36 884	30 779	130 5
6	13 202	12 873	18 654	44 277	22 45	152 95
7	11 128	14 165	18 227	51 846	21 945	174 89
8	8 904	15 178	17 805	59 602	21 458	196 35
9	6 567	15 896	17 398	67 551	20 999	217 35
10	4 675	16 45	17 15	74 134	16 896	234 25
11	2 757	16 456	16 894	80 488	15 827	250 07
12	995	15 949	16 333	86 429	13 83	263 91
13	- 455	15 026	15 506	91 735	11 135	275 04
14	-1 472	14 22	14 664	95 911	7 836	282 88
15	-2 275	13 284	13 886	99 722	6 412	289 29
16	-2 853	12 273	13 039	103 08	4 993	294 28
17	-3 205	11 241	12 144	105 91	3 638	297 92
18	-3 007	10 749	11 425	105 63	- 32	297 6
19	-2 928	10 195	10 885	106 02	408	298 01
20	-2 979	9 612001	10 336	107 22	1 112	299 12
21	-3 162	9 033	9 817001	109 29	1 742	300 86
22	-3 471	8 491901	9 372	112 23	2 254	303 12
23	-3 892	8 019	9 043899	115 89	2 612	305 73
24	-4 405	7 641	8 866901	119 96	2 793	308 52
25	-4 981	7 378	8 861	124 02	2 732	311 31
26	-5 676	7 415	9 121	127 43	2 474	313 78
27	-6 356	7 51	9 589	130 24	2 255	316 04
28	-7 016	7 662	10 114	132 48	1 938	318 04
29	-7 65	7 867	10 681	134 19	1 708	319 74
30	-9 093001	8 547	11 726	136 77	3 066	322 83
31	-10 42	9 402001	13 258	137 93	1 793	324 62
32	-11 61	10 415	14 816	138 1	31 7	324 94
33	-12 641	11 566	16 366	137 54	-1 31	323 63
34	-13 643	11 88	17 612	138 95	3 806	327 44
35	-14 711	11 954	18 523	140 9	5 843	333 28
36	-15 786	11 78	19 327	143 27	7 713	341
37	-16 807	11 361	19 992	145 94	9 323	350 32
38	-18 687	9 2	20 558	153 78	28 933	379 26
39	-20 082	6 694	20 999	161 56	29 928	404 19
40	-20 926	3 956	21 232	169 29	30 404	439 59
41	-21 184	1 113	21 255	176 99	30 353	469 95
42	-21 292	-1 528	21 28	184 1	28 111	498 06
43	-21 023	-4 157	21 389	191 18	28 265	526 32
44	-20 383	-6 719	21 446	198 24	28 334	554 66
45	-19 384	-9 163	21 451	205 3	28 332	583

46	-18 576	-10 703	21 44	209 95	18 55	601 65
47	-17 614	-12 155	21 42	214 6	18 656	620 3
48	-16 509	-13 504	21 365	219 28	18 609	638 91
49	-15 274	-14 733	21 275	223 96	18 51	657 4
50	-13 956	-16 032	21 239	228 95	19 653	677 08
51	-12 412	-17 07	21 181	233 97	19 644	696 7
52	-10 698	-17 805	20 939	239	19 224	715 95
53	-8 876001	-18 21	20 515	244 01	18 404	734 36
54	-7 702	-18 043	19 938	246 88	9 961001	744 32
55	-6 676	-17 506	19 177	249 12	7 186	751 5
56	-5 929	-16 686	18 222	250 43	3 805	755 31
57	-5 545	-15 709	17 183	250 55	307	755 62
58	-5 187	-14 624	16 087	250 47	- 195	755 42
59	-4 943	-13 521	14 956	249 91	-1 076	754 34
60	-4 814	-12 414	13 856	248 8	-1 868	752 48
61	-4 799	-11 313	12 802	247 01	-2 565	749 91
62	-3 704	-10 606	11 761	250 74	4 512	754 42
63	-2 413	-10 294	10 904	256 8	6 287	760 71
64	-1 094	-10 422	10 527	264	6 958	767 67
65	078	-10 967	10 724	270 4	6 427	774 1
66	1 082	-11 448	11 233	275 4	5 498	779 6
67	2 028	-11 914	11 792	279 66	5 172	784 77
68	2 91	-12 363	12 393	283 24	4 806	789 57
69	3 722	-12 792	13 012	286 22	4 398	793 97
70	5 379	-13 729	14 034	291 39	8 887	802 86
71	7 19	-14 421	15 43	296 49	10 604	813 47
72	9 116901	-14 845	16 768	301 55	12 406	825 87
73	11 118	-14 982	18 039	306 57	14 26	840 13
74	13 206	-14 705	19 211	311 92	17 226	857 36
75	15 225	-13 872	20 181	317 66	20 392	877 75
76	17 016	-12 519	20 861	323 65	22 771	900 52
77	18 438	-10 727	21 228	329 8	24 191	924 71
78	19 699	-8 224	21 339	337 33	29 923	954 64
79	20 605	-5 567	21 346	344 88	29 984	984 62
80	21 136	-2 807	21 333	352 43	29 997	1014 6
81	21 282	0	21 302	360	29 964	1044 5

TOTAL AREA OF THIS INTERMEDIATE SURFACE (AT Z = 10) = 1044 588 mm Square

---

REDUCTION RATIO OF AREA AT THIS SURFACE = 46 79639 %

REDUCTION RATIO OF AREA AT BOTTOM SURFACE = 58 37781 %

TABLE 11

Shows the calculated angles alpha and beta, machining area and machining time for the circle to complex shape.

SEGMENT NUMBER	ALFA (Degrees)	BETA (Degrees)	MACHINING AREA (mm Sq)	MACHINING TIME (Seconds)	TOTAL M AREA mm Sq	TOTAL M TIME (Sec)
1	0	7 3057	877 5	65 8125	877 5	65 8125
2	8 8808	8 3806	128 962	9 67221	1006 463	75 4847
3	45388	9 6966	128 962	9 67221	1135 426	85 1569
4	1 1763	11 179	128 962	9 67221	1264 389	94 8291
5	2 3199	12 733	128 962	9 67221	1393 352	104 501
6	4 6238	12 839	107 269	8 04521	1500 621	112 546
7	6 9056	12 636	107 269	8 04518	1607 89	120 591
8	9 1195	12 133	107 269	8 04519	1715 16	128 637
9	11 223	11 345	107 269	8 04520	1822 429	136 682
10	12 908	9 3364	94 0500	7 05375	1916 479	143 735
11	14 853	7 0551	94 0501	7 05376	2010 529	150 789
12	16 946	4 2782	94 0501	7 05375	2104 579	157 843
13	18 979	85079	94 0501	7 05376	2198 63	164 897
14	20 019	-3 3204	84 0273	6 30205	2282 657	171 199
15	20 536	-7 7135	84 0273	6 30205	2366 684	177 501
16	20 467	-12 237	84 0274	6 30205	2450 712	183 803
17	19 745	-16 786	84 0275	6 30206	2534 739	190 105
18	20 217	-17 708	22 2740	1 67055	2557 013	191 776
19	20 781	-18 401	22 2739	1 67054	2579 287	193 446
20	21 381	-18 856	22 2739	1 67054	2601 561	195 117
21	21 958	-19 083	22 2739	1 67054	2623 835	196 787
22	22 456	-19 103	22 2738	1 67054	2646 109	198 458
23	22 825	-18 947	22 2740	1 67055	2668 383	200 128
24	23 024	-18 658	22 2738	1 67053	2690 657	201 799
25	23 019	-18 282	22 2740	1 67055	2712 931	203 469
26	22 501	-17 763	24 6829	1 85121	2737 614	205 321
27	21 870	-17 266	24 6828	1 85121	2762 297	207 172
28	21 126	-16 796	24 6830	1 85122	2786 98	209 023
29	20 271	-16 364	24 6827	1 85120	2811 662	210 874
30	18 558	-14 579	49 3219	3 69914	2860 985	214 573
31	16 482	-12 934	49 3218	3 69913	2910 306	218 272
32	14 058	-11 472	49 3220	3 69915	2959 628	221 972
33	11 310	-10 238	49 3217	3 69912	3008 95	225 t71
34	10 107	-8 9527	34 8708	2 61531	3043 821	228 286
35	9 3470	-7 4954	34 8705	2 61529	3078 692	230 901
36	9 0545	-5 9889	34 8709	2 61531	3113 562	233 517
37	9 2215	-4 5598	34 8716	2 61537	3148 434	236 13□
38	8 3019	-4 6754	116 994	8 77456	3265 428	244 907
39	7 6034	-5 0310	116 994	8 77456	3382 422	253 681
40	7 0009	-5 7004	116 994	8 77456	3499 416	262 456
41	6 3516	-6 7150	116 994	8 77456	3616 411	271 230
42	5 1600	-7 2098	111 182	8 33867	3727 593	279 569
43	3 9025	-7 6057	111 182	8 33867	3838 775	287 908
44	2 5839	-7 8925	111 182	8 33867	3949 958	296 246
45	1 2110	-8 0599	111 182	8 33866	4061 14	304 585
46	-1 6594	-7 0715	87 4914	6 56186	4148 631	311 147
47	-4 3060	-5 6250	87 4916	6 56187	4236 123	317 709
48	-6 6589	-3 7666	87 4911	6 56183	4323 614	324 271
49	-8 6616	-1 5532	87 4916	6 56187	4411 106	330 832
50	-9 8824	1 0202	90 7280	6 80460	4501 834	337 637
51	-10 905	3 5789	90 7278	6 80458	4592 562	344 442

```
52    -11 759  , 6 1281  , 90 7279  , 6 80459     4683 29  , 351 246
53    ,-12 463    8 6816  : 90 7276  : 6 80457     4774 017    358 051
54    -12 995     7 8022  , 40 6693    3 05020  , 4814 687    361 101
55    ,-14 174  , 7 1915    40 6694  , 3 05020     4855 356    364 151
56    ,-15 823  , 7 0922  , 40 6692  , 3 05019     4896 026    367 201
57    -17 688  , 7 6556  : 40 6693  . 3 05020  , 4936 695    370 252
58    ,-19 667  , 8 2401  , 43 1970  , 3 23977  , 4979 892    373 491
59    :-21 593  , 9 0058    43 1970  . 3 23977  , 5023 09  ,  376 731
60    -23 442  , 9 9432  , 43 1969  : 3 23977  : 5066 286    379 971
61    '-25 197  ' 11 040  ' 43 1969  ' 3 23977  , 5109 483,   383 211
62    -26 245  : 10 312  , 44 1705    3 31279  , 5153 654,   386 524
63    ,-26 622  , 9 3057    44 1705  : 3 31279     5197 824    389 836
64    -26 268    8 3005  ' 44 1705  , 3 31279  , 5241 994,   393 149
65    '-25 209  , 7 5760  ' 44 1697  : 3 31272  , 5286 164    396 462
66    ,-23 649    9 6589  , 62 3714  : 4 67786  , 5348 536    401 140
67    :-21 763  , 11 797  , 62 3714  , 4 67786  , 5410 907    405 818
68    ,-19 543  . 13 968  , 62 3716  : 4 67787     5473 279    410 495
69    :-16 985  , 16 143  , 62 3714  , 4 67786  , 5535 651,   415 173
70    ,-13 101  , 16 747  ' 87 4640  , 6 55980  , 5623 115:   421 733
71    :-9 2620  , 16 814  : 87 4638  : 6 55978  , 5710 578:   428 293
72    ,-5 5778  , 16 372  , 87 4639  , 6 55979  : 5798 042    434 853
73    :-2 1464    15 472  : 87 4637  : 6 55978  , 5885 506,   441 412
74    ,   72391  , 14 076    88 5854  , 6 64391  , 5974 092,   448 056
75    :  2 7095  , 12 478  ' 88 5853  : 6 64390  : 6062 677,   454 700
76    , 3 8539  : 10 982  , 88 5856  : 6 64392  , 6151 262    461 344
77    , 4 2927  , 9 8581  : 88 5855  : 6 64391  : 6239 848,   467 988
78    : 3 4616  , 8 7049  : 101 594  : 7 61956  , 6341 442,   475 608
79    : 2 4212  , 7 8751  : 101 594  , 7 61955  , 6443 036    483 227
80    , 1 2422  : 7 4021  : 101 594  : 7 61955  , 6544 631'   490 847
81    :-1 8096  : 7 3057  : 101 594  : 7 61955  : 6646 225,   498 466
82    , 0         0       , 877 5   , 65 8125  : 7523 725'   564 279
```

TOTAL AREA OF 7523 725 mm Sqr   NEEDS MACHINING TIME OF
9 MINUTES AND 24 27 SECONDS AT THE FEED RATE OF   800   mm Sqr /Min

TABLE 12

Shows the X and Y coordinates, linear travelling distance, machining area and machining time for the spur gear.

SEGMENT NUMBER	X (m m)	Y (m m)	TOTAL TRAVEL (m m)	MACH AREA (m m Sq)	MACHINING TIME Seconds
1	4 1044	-28 202	42 060	461 82	115 4188
2	4 1928	-30 022	1 8215	54 646	6 557614
3	4 5021	-31 817	1 8215	54 647	6 557663
4	5 0271	-33 561	1 8215	54 647	6 557646
5	5 7602	-35 229	1 8215	54 646	6 557611
6	6 6904	-36 795	1 8215	54 647	6 557657
7	7 8039	-38 237	1 8215	54 647	6 557647
8	9 0844	-39 532	1 8215	54 646	6 557636
9	10 512	-40 663	1 8215	54 647	6 557654
10	11 380	-40 428	89879	26 963	3 235652
11	12 242	-40 175	89877	26 963	3 235603
12	13 099	-39 904	89878	26 963	3 235629
13	13 950	-39 615	89876	26 962	3 235554
14	14 505	-37 880	1 8215	54 646	6 557632
15	14 846	-36 090	1 8215	54 646	6 557613
16	14 966	-34 273	1 8215	54 646	6 557589
17	14 865	-32 454	1 8215	54 646	6 557616
18	14 543	-30 661	1 8215	54 646	6 557628
19	14 006	-28 921	1 8215	54 646	6 557619
20	13 262	-27 258	1 8215	54 646	6 557606
21	12 321	-25 698	1 8215	54 646	6 557589
22	13 445	-25 129	1 2597	37 790	4 534918
23	14 542	-24 510	1 2596	37 790	4 534883
24	15 611	-23 843	1 2596	37 790	4 534869
25	16 649	-23 130	1 2596	37 790	4 534889
26	17 655	-22 372	1 2596	37 790	4 534906
27	18 642	-23 903	1 8215	54 647	6 557674
28	19 807	-25 303	1 8215	54 646	6 557619
29	21 134	-26 551	1 8215	54 647	6 557643
30	22 603	-27 629	1 8215	54 646	6 557637
31	24 191	-28 520	1 8215	54 647	6 557654
32	25 876	-29 212	1 8215	54 646	6 55763
33	27 633	-29 694	1 8215	54 646	6 557632
34	29 435	-29 958	1 8215	54 646	6 557631
35	30 070	-29 322	89879	26 963	3 235677
36	30 690	-28 671	89878	26 963	3 235631
37	31 297	-28 008	89877	26 963	3 23559
38	31 889	-27 332	89877	26 963	3 235598
39	31 502	-25 552	1 8215	54 646	6 557586
40	30 902	-23 832	1 8215	54 647	6 55764
41	30 098	-22 198	1 8215	54 646	6 557594
42	29 101	-20 673	1 8215	54 646	6 557626
43	27 926	-19 281	1 8215	54 646	6 557616
44	26 590	-18 042	1 8215	54 646	6 557604
45	25 114	-16 975	1 8215	54 646	6 557633
46	23 520	-16 094	1 8215	54 646	6 55759
47	24 208	-15 039	1 2596	37 790	4 534892
48	24 849	-13 955	1 2596	37 790	4 534895
49	25 441	-12 843	1 2596	37 790	4 534894
50	25 984	-11 707	1 2596	37 790	4 534882
51	26 476	-10 547	1 2596	37 790	4 534878
52	28 096	-11 380	1 8215	54 647	6 557644
53	29 805	-12 009	1 8215	54 647	6 557647
54	31 578	-12 427	1 8215	54 646	6 557632
55	33 389	-12 626	1 8215	54 646	6 557638
56	35 211	-12 603	1 8215	54 647	6 557648
57	37 016	-12 360	1 8215	54 646	6 557618
58	38 778	-11 899	1 8215	54 647	6 557674
59	40 471	-11 237	1 8215	54 647	6 557642

60	40 702	-10 358	89879	26 963	3 235656
61	40 914	-9 4852	89878	26 963	3 235616
62	41 108	-8 6076	89878	26 963	3 235615
63	41 283	-7 7259	89877	26 963	3 235584
64	40 058	-6 3777	1 8215	54 646	6 557616
65	38 678	-5 1882	1 8215	54 646	6 557602
66	37 164	-4 1752	1 8215	54 647	6 557642
67	35 539	-3 3536	1 8215	54 646	6 557586
68	33 825	-2 7355	1 8215	54 646	6 557619
69	32 049	-2 3302	1 8215	54 646	6 55761
70	30 237	-2 1436	1 8215	54 646	6 557618
71	28 416	-2 1785	1 8215	54 646	6 557598
72	28 485	- 92072	1 2596	37 790	4 534899
73	28 497	33890	1 2596	37 790	4 534888
74	28 455	1 5978	1 2596	37 790	4 534888
75	28 356	2 8537	1 2596	37 790	4 534888
76	28 202	4 1039	1 2596	37 790	4 534891
77	30 022	4 1928	1 8215	54 646	6 557614
78	31 817	4 5021	1 8215	54 647	6 557662
79	33 561	5 0271	1 8215	54 646	6 557636
80	35 229	5 7601	1 8215	54 646	6 55762
81	36 795	6 6903	1 8215	54 647	6 55764
82	38 237	7 8039	1 8215	54 647	6 557645
83	39 532	9 0843	1 8215	54 646	6 557633
84	40 663	10 512	1 8215	54 646	6 557633
85	40 428	11 380	89878	26 963	3 235641
86	40 176	12 242	89877	26 963	3 235595
87	39 904	13 099	89878	26 963	3 235626
88	39 615	13 950	89878	26 963	3 235621
89	37 880	14 505	1 8215	54 646	6 557632
90	36 090	14 846	1 8215	54 646	6 557613
91	34 273	14 966	1 8215	54 646	6 557633
92	32 454	14 865	1 8215	54 646	6 557617
93	30 661	14 543	1 8215	54 646	6 557594
94	28 921	14 006	1 8215	54 647	6 557652
95	27 258	13 262	1 8215	54 647	6 557644
96	25 698	12 321	1 8215	54 646	6 55763
97	25 129	13 445	1 2596	37 790	4 534902
98	24 510	14 542	1 2596	37 790	4 5349
99	23 843	15 611	1 2596	37 790	4 534898
100	23 130	16 649	1 2596	37 790	4 534889
101	22 372	17 655	1 2596	37 790	4 53486
102	23 903	18 642	1 8215	54 647	6 557639
103	25 303	19 807	1 8215	54 647	6 557673
104	26 551	21 134	1 8215	54 646	6 557613
105	27 629	22 603	1 8215	54 647	6 557668
106	28 520	24 191	1 8215	54 646	6 557603
107	29 212	25 876	1 8215	54 647	6 557546
108	29 694	27 633	1 8215	54 647	6 557662
109	29 958	29 435	1 8215	54 646	6 557635
110	29 322	30 070	89878	26 963	3 235619
111	28 671	30 690	89877	26 963	3 235601
112	28 008	31 297	89878	26 963	3 235039
113	27 332	31 889	89877	26 963	3 235582
114	25 552	31 502	1 8215	54 647	6 557654
115	23 832	30 902	1 8215	54 647	6 55764
116	22 198	30 098	1 8215	54 647	6 55764
117	20 673	29 101	1 8215	54 646	6 55761
118	19 281	27 926	1 8215	54 646	6 557639
119	18 042	26 590	1 8215	54 647	6 557664
120	16 975	25 114	1 8215	54 646	6 557613
121	16 094	23 520	1 8215	54 646	6 557639
122	15 039	24 208	1 2596	37 790	4 534885
123	13 955	24 849	1 2596	37 790	4 534916
124	12 843	25 441	1 2596	37 790	4 534878
125	11 707	25 984	1 2596	37 790	4 534894
126	10 547	26 476	1 2596	37 790	4 534899
127	11 380	28 096	1 8215	54 647	6 557644
128	12 009	29 805	1 8215	54 647	6 557647
129	12 427	31 578	1 8215	54 646	6 557634
130	12 626	33 389	1 8215	54 646	6 557638

131	12 603	35 211	1 8215	' 54 647	6 557649
132	12 360	37 016	1 8215	54 646	6 557627
133	11 899	, 38 778	1 8215	54 646	6 55762
134	11 227	40 471	1 8215	54 647	6 557656
135	10 358	, 40 702	89877	26 963	, 3 235597
136	9 4853	40 914	89878	26 963	3 235626
137	, 8 6076	41 108	89878	26 963	3 235609
138	7 7259	41 283	89879	, 26 963	3 235663
139	6 3777	40 058	1 8215	, 54 646	6 557625
140	5 1882	38 678	1 8215	54 647	6 557641
141	4 1752	37 164	1 8215	54 647	6 557649
142	3 3536	35 539	1 8215	54 647	' 6 557657
143	2 7355	33 825	1 8215	54 646	6 557619
144	' 2 3302	32 049	1 8215	54 646	6 557633
145	2 1436	30 237	, 1 8215	54 647	' 6 557658
146	2 1785	28 416	1 8215	54 646	6 557633
147	92074	' 28 485	1 2596	37 790	' 4 534898
148	- 33888	28 497	1 2596	37 790	4 5349
149	,-1 5978	' 28 455	1 2596	37 790	' 4 534901
150	'-2 8536	28 356	1 2596	37 790	4 534901
151	-4 1039	28 202	1 2597	37 791	4 534935
152	-4 1928	30 022	1 8215	54 647	6 557648
153	-4 5021	31 817	1 8215	54 646	6 557629
154	-5 0271	' 33 561	1 8215	54 646	6 557637
155	-5 7602	35 229	1 8215	54 647	6 557647
156	-6 6903	36 795	1 8215	54 646	6 557622
157	-7 8039	38 237	1 8215	54 647	6 557645
158	-9 0843	39 532	1 8215	, 54 646	' 6 557632
159	-10 512	40 663	1 8215	54 647	; 6 557654
160	-11 380	40 428	89877	26 963	3 235605
161	-12 242	40 176	89877	26 963	3 235595
162	-13 099	39 904	89878	26 963	3 235629
163	-13 950	' 39 615	89876	26 962	3 235541
164	-14 505	37 880	1 8215	54 646	6 557619
165	-14 846	36 090	1 8215	54 647	6 557654
166	-14 966	34 273	1 8215	54 647	6 557657
167	-14 865	32 454	1 8215	54 647	6 557657
168	-14 543	30 661	1 8215	54 646	6 5576
169	-14 006	28 921	1 8215	54 647	6 557658
170	-13 262	27 258	1 8215	54 646	6 557637
171	-12 321	25 698	1 8215	54 646	6 557637
172	-13 445	25 129	1 2596	37 790	4 534899
173	-14 542	24 510	1 2596	37 790	4 534853
174	-15 611	23 843	1 2596	37 790	4 534895
175	-16 649	23 130	1 2596	37 790	4 534891
176	-17 655	22 372	1 2597	37 791	4 534944
177	-18 642	23 404	1 8215	54 646	6 557626
178	-19 807	, 25 303	1 8215	54 647	6 557645
179	-21 134	26 551	1 8215	54 647	6 557643
180	-22 603	27 629	1 8215	54 646	6 557637
181	-24 191	28 520	1 8215	54 647	6 557654
182	-25 876	, 29 212	1 8215	54 646	6 55763
183	-27 633	29 694	1 8215	54 646	6 557634
184	-29 435	29 958	1 8215	54 647	6 557671
185	-30 070	29 322	89878	26 963	3 235623
186	-30 690	28 671	89878	26 963	3 235626
187	-31 297	28 008	89877	26 963	3 235586
188	-31 889	27 332	89876	26 963	3 23556
189	-31 502	25 552	1 8215	54 647	6 557654
190	-30 902	23 832	1 8215	54 647	6 55764
191	,-30 098	22 198	1 8215	54 647	6 557642
192	-29 101	20 673	1 8215	, 54 647	, 6 557645
193	-27 926	19 281	1 8215	' 54 647	6 557643
194	,-26 590	, 18 042	1 8215	54 646	6 557638
195	-25 114	16 975	, 1 8215	54 646	6 557636
196	-23 520	, 16 094	1 8215	¦ 54 646	6 557622
197	'-24 208	' 15 039	' 1 2596	37 790	, 4 534891
198	¦-24 849	¦ 13 955	' 1 2596	37 790	4 534899
199	-25 441	12 843	1 2596	¦ 37 790	¦ 4 534878
200	¦-25 984	, 11 707	¦ 1 2596	¦ 37 790	' 4 534891
201	-26 476	10 547	, 1 2597	37 791	' 4 534995

202	-28.096	11.380	1.8215	54.647	6.557644
203	-29.805	12.009	1.8215	54.647	6.557647
204	-31.578	12.427	1.8215	54.647	6.557641
205	-33.389	12.626	1.8215	54.646	6.557634
206	-35.211	12.603	1.8215	54.646	6.557607
207	-37.016	12.360	1.8215	54.647	6.557654
208	-38.778	11.899	1.8215	54.646	6.557634
209	-40.471	11.227	1.8215	54.647	6.557654
210	-40.702	10.358	.89878	26.963	3.235633
211	-40.914	9.4853	.89877	26.963	3.235599
212	-41.108	8.6076	.89878	26.963	3.235616
213	-41.283	7.7260	.89875	26.962	3.235523
214	-40.058	6.3777	1.8215	54.646	6.557628
215	-38.678	5.1883	1.8215	54.647	6.557646
216	-37.164	4.1752	1.8215	54.647	6.557639
217	-35.539	3.3536	1.8215	54.646	6.557637
218	-33.825	2.7355	1.8215	54.647	6.557645
219	-32.049	2.3302	1.8215	54.646	6.557637
220	-30.237	2.1436	1.8215	54.646	6.557624
221	-28.416	2.1785	1.8215	54.646	6.557633
222	-28.485	.92075	1.2596	37.790	4.534883
223	-28.497	-.33887	1.2596	37.790	4.534888
224	-28.455	-1.5978	1.2596	37.790	4.534689
225	-28.356	-2.8536	1.2596	37.790	4.534888
226	-28.202	-4.1039	1.2597	37.791	4.534991
227	-30.022	-4.1923	1.8215	54.647	6.557648
228	-31.817	-4.5021	1.8215	54.646	6.557629
229	-33.561	-5.0271	1.8215	54.646	6.557636
230	-35.229	-5.7601	1.8215	54.647	6.557646
231	-36.795	-6.6903	1.8215	54.647	6.557656
232	-38.237	-7.8039	1.8215	54.647	6.557643
233	-39.532	-9.0843	1.8215	54.646	6.557633
234	-40.663	-10.512	1.8215	54.646	6.55763
235	-40.438	-11.380	.89878	26.963	3.235641
236	-40.176	-12.242	.89877	26.963	3.235607
237	-39.904	-13.099	.89878	26.963	3.235626
238	-39.615	-13.950	.89876	26.962	3.235553
239	-37.880	-14.505	1.8215	54.647	6.557671
240	-36.090	-14.846	1.8215	54.646	6.557613
241	-34.273	-14.966	1.8215	54.646	6.557616
242	-32.454	-14.865	1.8215	54.647	6.557657
243	-30.661	-14.543	1.8215	54.646	6.557634
244	-28.921	-14.006	1.8215	54.647	6.557658
245	-27.258	-13.262	1.8215	54.646	6.55762
246	-25.698	-12.321	1.8215	54.647	6.557666
247	-25.129	-13.445	1.2596	37.790	4.534868
248	-24.510	-14.542	1.2596	37.790	4.534886
249	-23.843	-15.611	1.2596	37.790	4.534895
250	-23.130	-16.649	1.2596	37.790	4.534891
251	-22.372	-17.655	1.2597	37.791	4.534989
252	-23.903	-18.642	1.8215	54.646	6.55762
253	-25.303	-19.807	1.8215	54.647	6.557641
254	-26.551	-21.134	1.8215	54.647	6.557641
255	-27.629	-22.603	1.8215	54.647	6.557641
256	-28.520	-24.191	1.8215	54.646	6.557633
257	-29.212	-25.876	1.8215	54.647	6.557646
258	-29.694	-27.633	1.8215	54.646	6.557632
259	-29.958	-29.435	1.8215	54.647	6.557664
260	-29.322	-30.070	.89878	26.963	3.235623
261	-28.671	-30.690	.89878	26.963	3.235626
262	-28.008	-31.297	.89877	26.963	3.23559
263	-27.332	-31.889	.89875	26.962	3.235529
264	-25.552	-31.502	1.8215	54.647	6.557646
265	-23.832	-30.902	1.8215	54.647	6.55764
266	-22.198	-30.098	1.8215	54.647	6.557642
267	-20.673	-29.101	1.8215	54.647	6.557651
268	-19.281	-27.926	1.8215	54.647	6.557643
269	-18.042	-26.590	1.8215	54.646	6.557634
270	-16.975	-25.114	1.8215	54.646	6.557607
271	-16.094	-23.520	1.8215	54.647	6.557642
272	-15.039	-24.208	1.2596	37.790	4.534901

273	-13 955	-24 849	1 2596	37 790	4 534899
274	-12 843	-25 441	1 2596	37 790	4 534878
275	-11 707	-25 984	1 2596	37 790	4 534891
276	-10 547	-26 476	1 2597	37 791	4 534963
277	-11 380	-28 096	1 8215	54 646	6 557614
278	-12 009	-29 805	1 8215	54 647	6 557649
279	-12 427	-31 578	1 8215	54 646	6 557633
280	-12 626	-33 389	1 8215	54 646	6 557634
281	-12 603	-35 211	1 8215	54 647	6 557649
282	-12 360	-37 016	1 8215	54 647	6 557654
283	-11 899	-38 778	1 8215	54 646	6 557594
284	-11 227	-40 471	1 8215	54 646	6 557616
285	-10 358	-40 702	89879	26 963	3 235674
286	-9 4853	-40 914	89877	26 963	3 235599
287	-8 6076	-41 108	89878	26 963	3 235619
288	-7 7260	-41 283	89876	26 962	3 23555
289	-6 3777	-40 058	1 8215	54 646	6 557632
290	-5 1883	-38 678	1 8215	54 647	6 55764
291	-4 1752	-37 164	1 8215	54 647	6 55765
292	-3 3536	-35 539	1 8215	54 647	6 557658
293	-2 7355	-33 825	1 8215	54 646	6 55762
294	-2 3302	-32 049	1 8215	54 646	6 557636
295	-2 1436	-30 237	1 8215	54 647	6 557657
296	-2 1785	-28 416	1 8215	54 646	6 557633
297	- 92075	-28 485	1 2596	37 790	4 534913
298	33886	-28 497	1 2596	37 790	4 534888
299	1 5978	-28 455	1 2596	37 790	4 534886
300	2 8536	-28 356	1 2596	37 790	4 534891
301	4 1039	-28 202	1 2597	37 791	4 535034
302	0	-60	32 060	961 82	115 4188

TOTAL AREA OF 15977 55 mm   Sqr   NEEDS MACHINING TIME   OF
31 MINUTES AND 57 30 SECONDS AT THE FEED RATE OF   500   mm   Sqr/Min
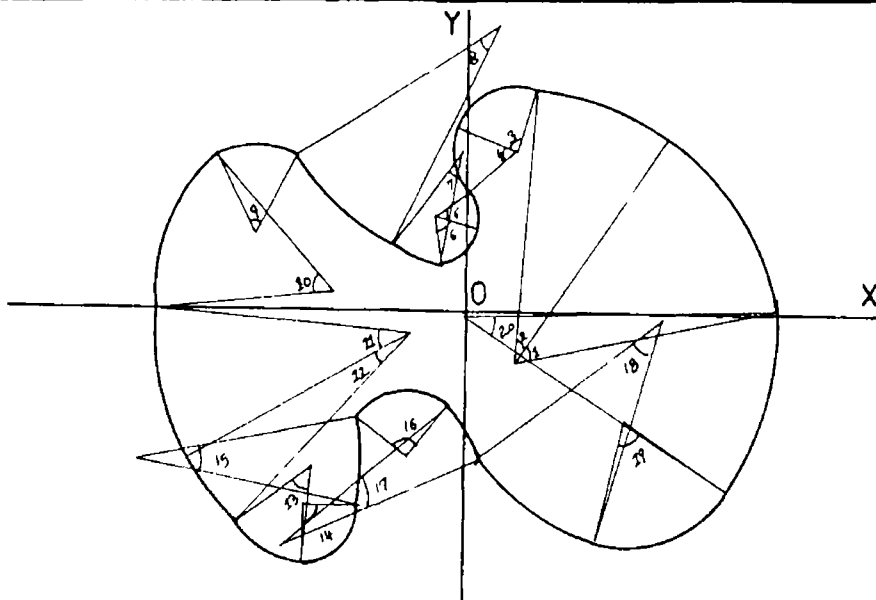
Figure 59a
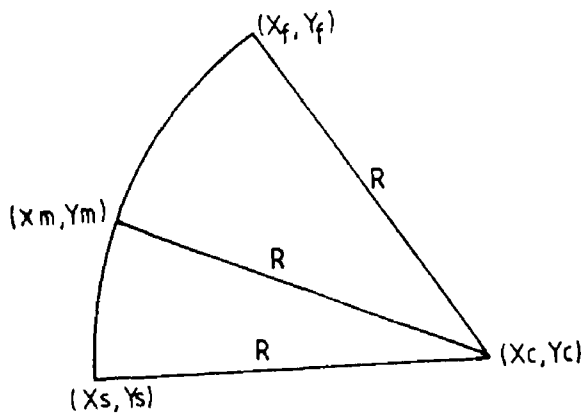
Figure 59b
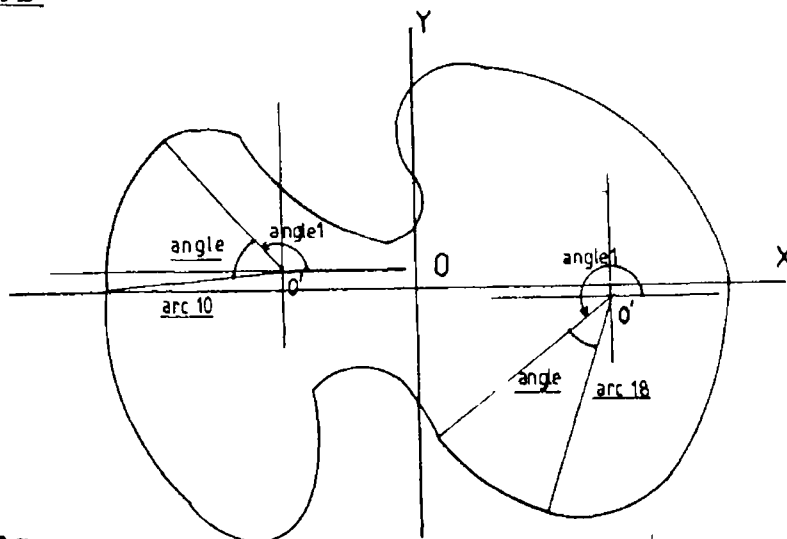
Figure 59c

Figure 59. Shows the construction of the complex shape

Figure 60a
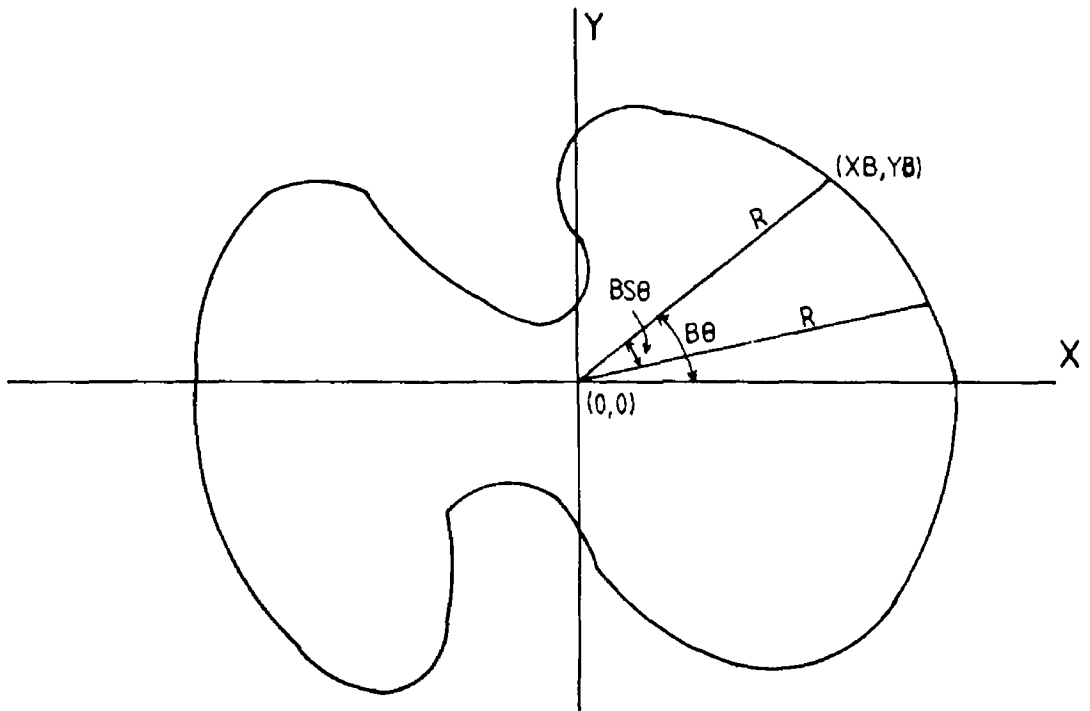
Figure 60b
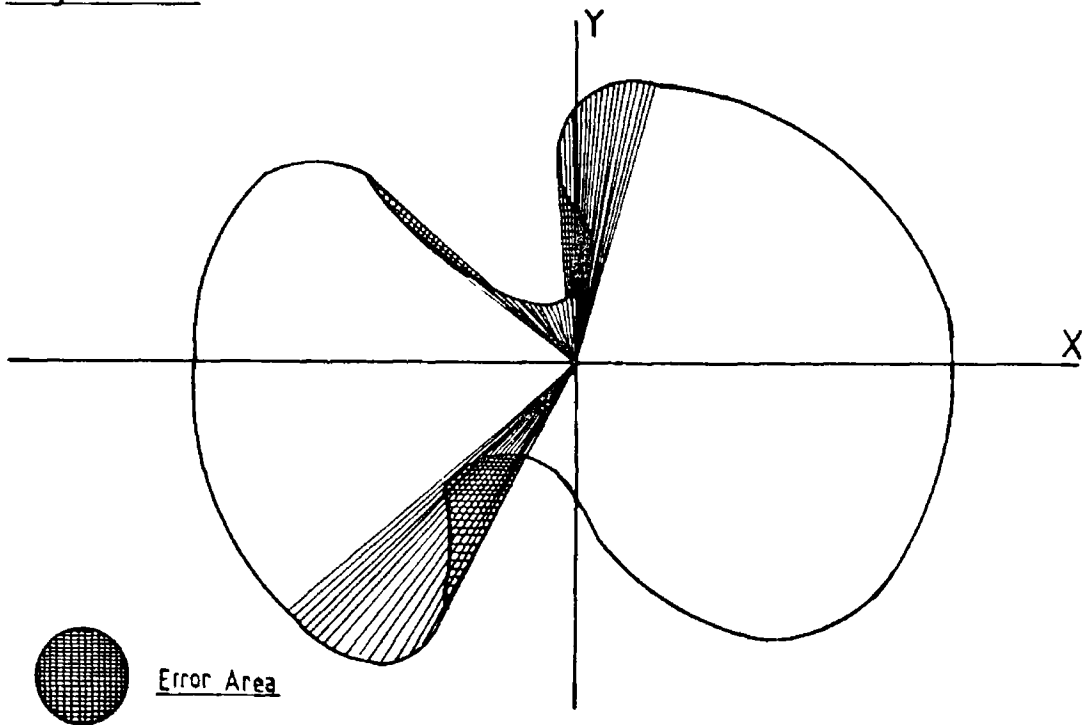
Error Area

Figure 60. Shows the area calculation and error area of the complex shape
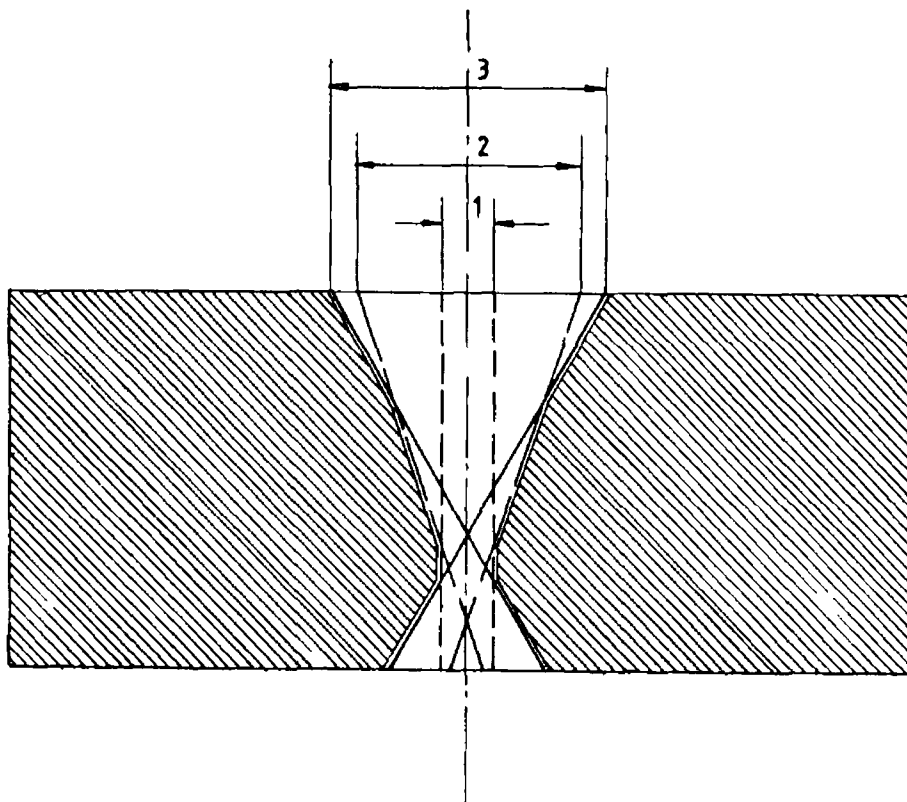
Figure 61. A representation of a taper die design showing three stages of manufacturing
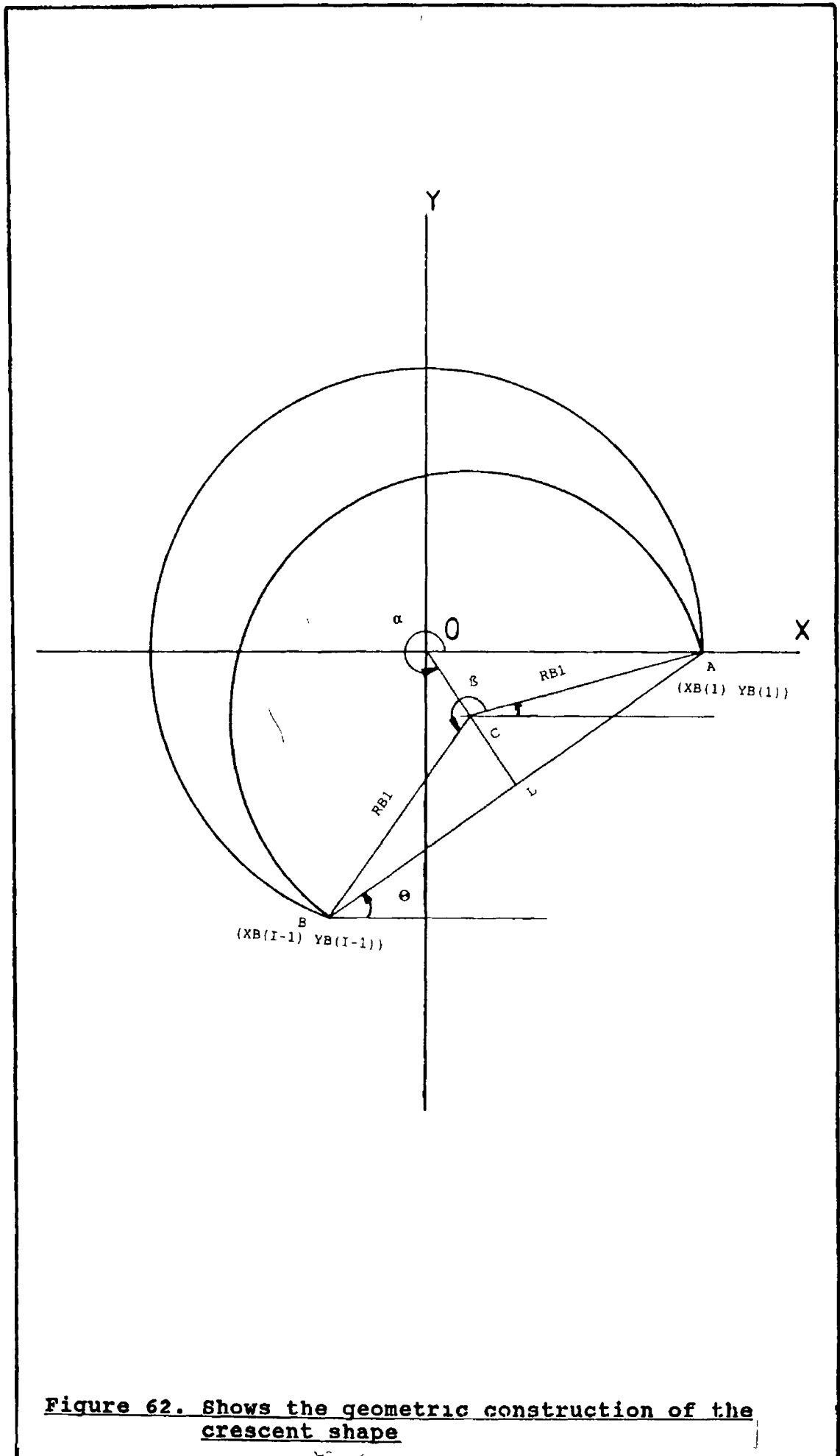
Figure 62. Shows the geometric construction of the crescent shape
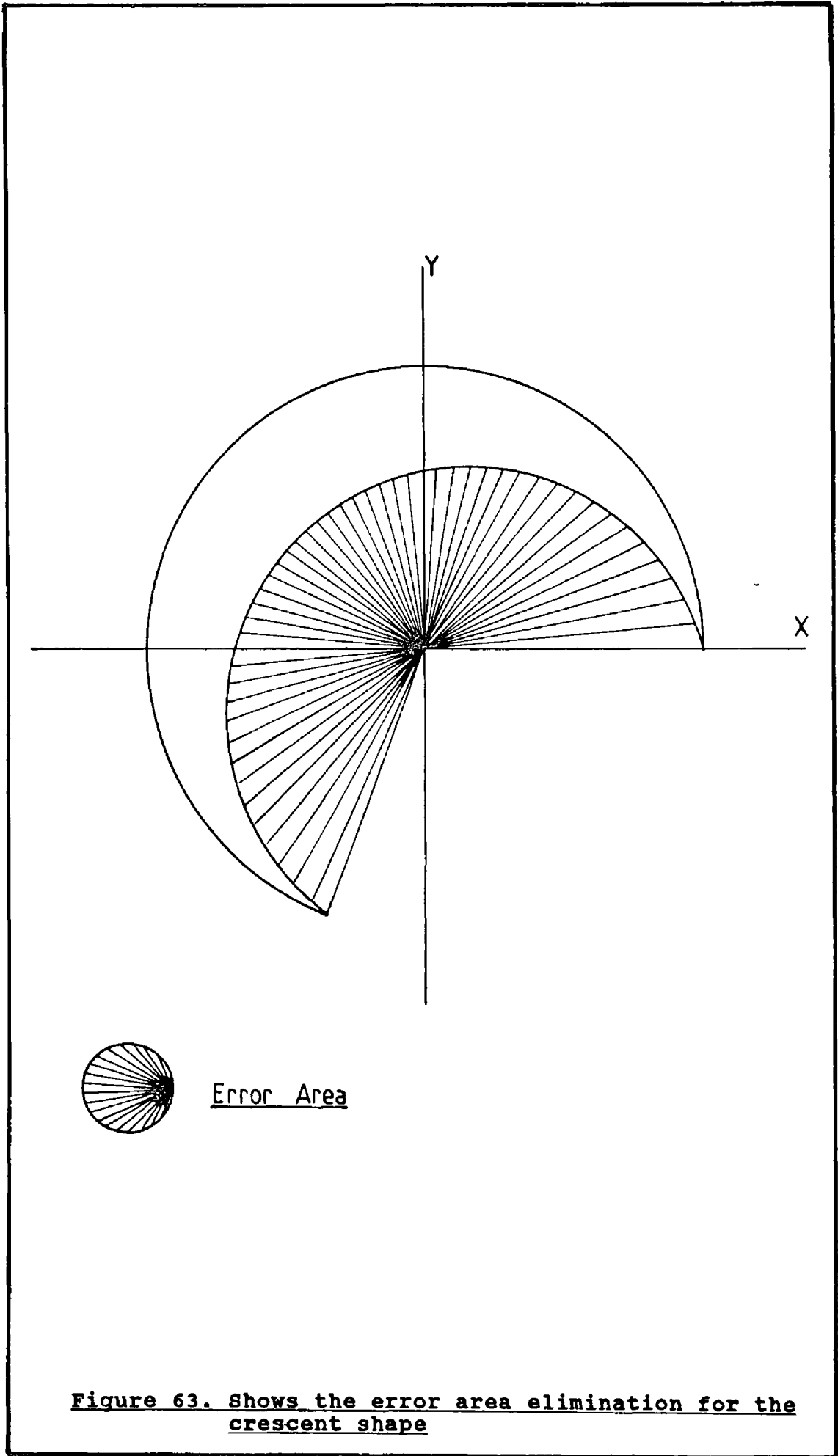
Figure 63. Shows the error area elimination for the crescent shape
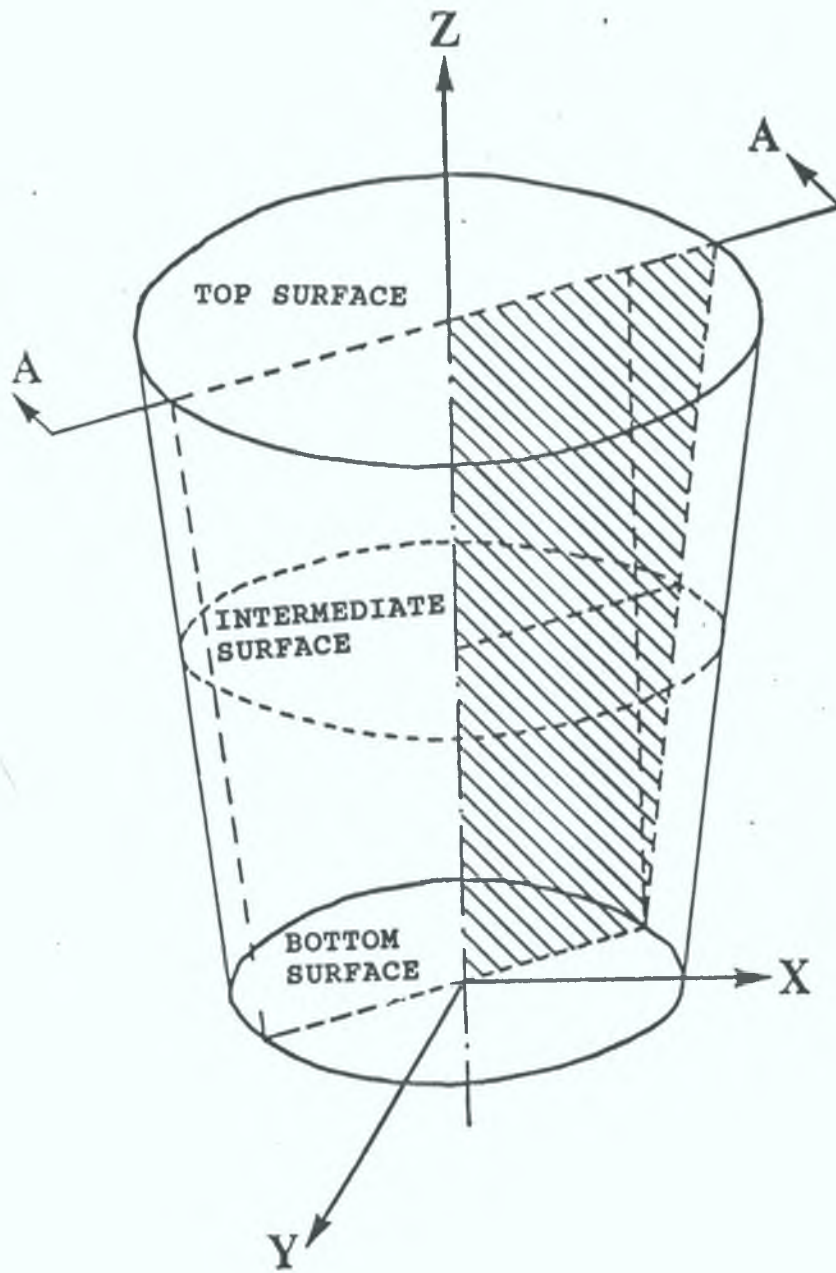
Figure 64. Shows the 3-d die profile for the circle to circle shape
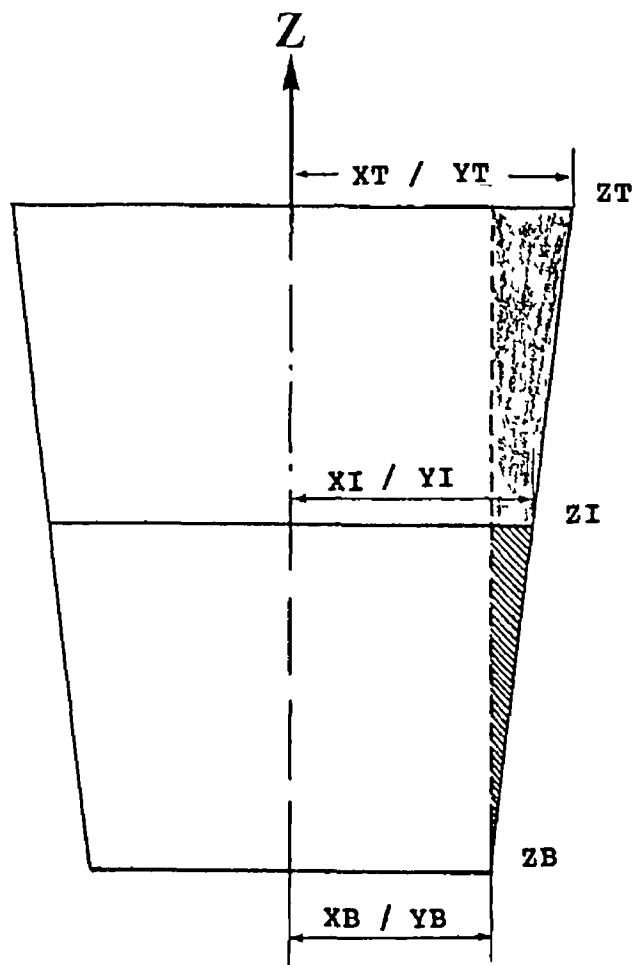
$$\frac{(\ XT \ - \ XB \ )}{(\ ZT \ - \ ZB \ )} \ = \ \frac{(\ XI \ - \ XB \ )}{(\ ZI \ - \ ZB \ )}$$

$$\frac{(\ YT \ - \ YB \ )}{(\ ZT \ - \ ZB \ )} \ = \ \frac{(\ YI \ - \ YB \ )}{(\ ZI \ - \ ZB \ )}$$

Figure 65. Shows the section A-A

TOP SURFACE

BOTTOM SURFACE

INTERMEDIATE SURFACES
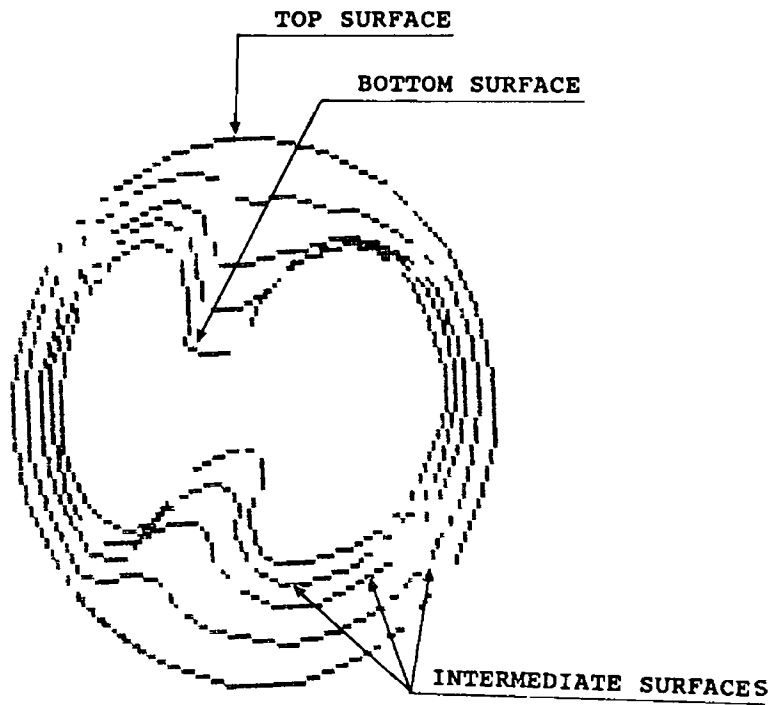
Figure 66. A typical printout from the graphical drawing generated by computer for top, bottom and intermediate sections
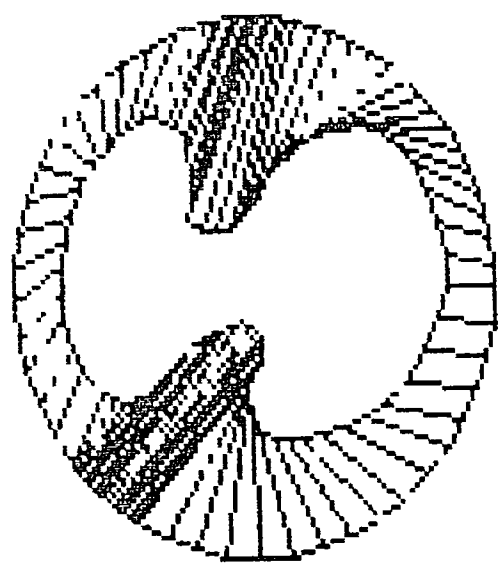
Figure 67. Shows the wire cutting path between top and bottom surfaces
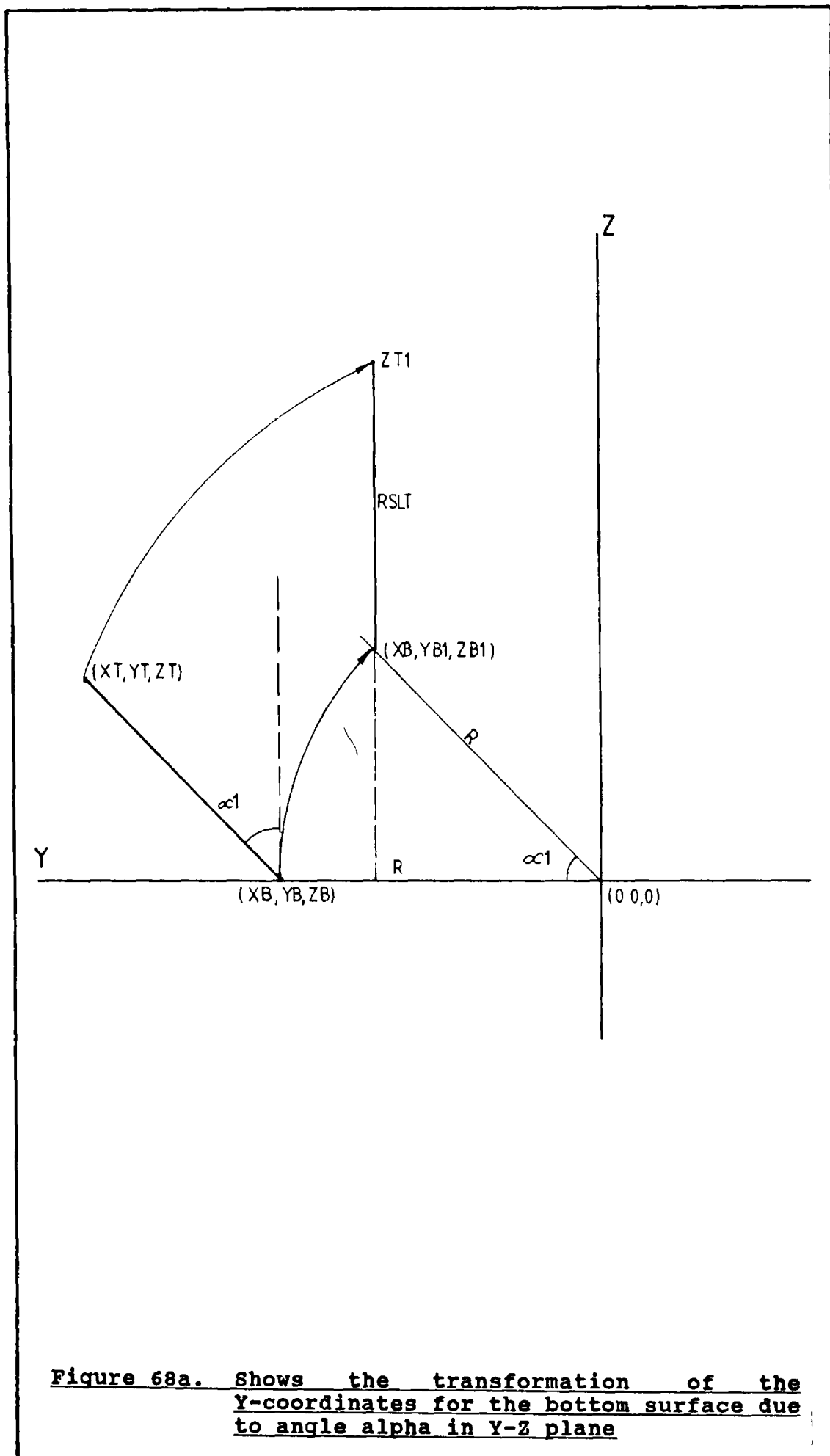
Figure 68a. Shows the transformation of the Y-coordinates for the bottom surface due to angle alpha in Y-Z plane
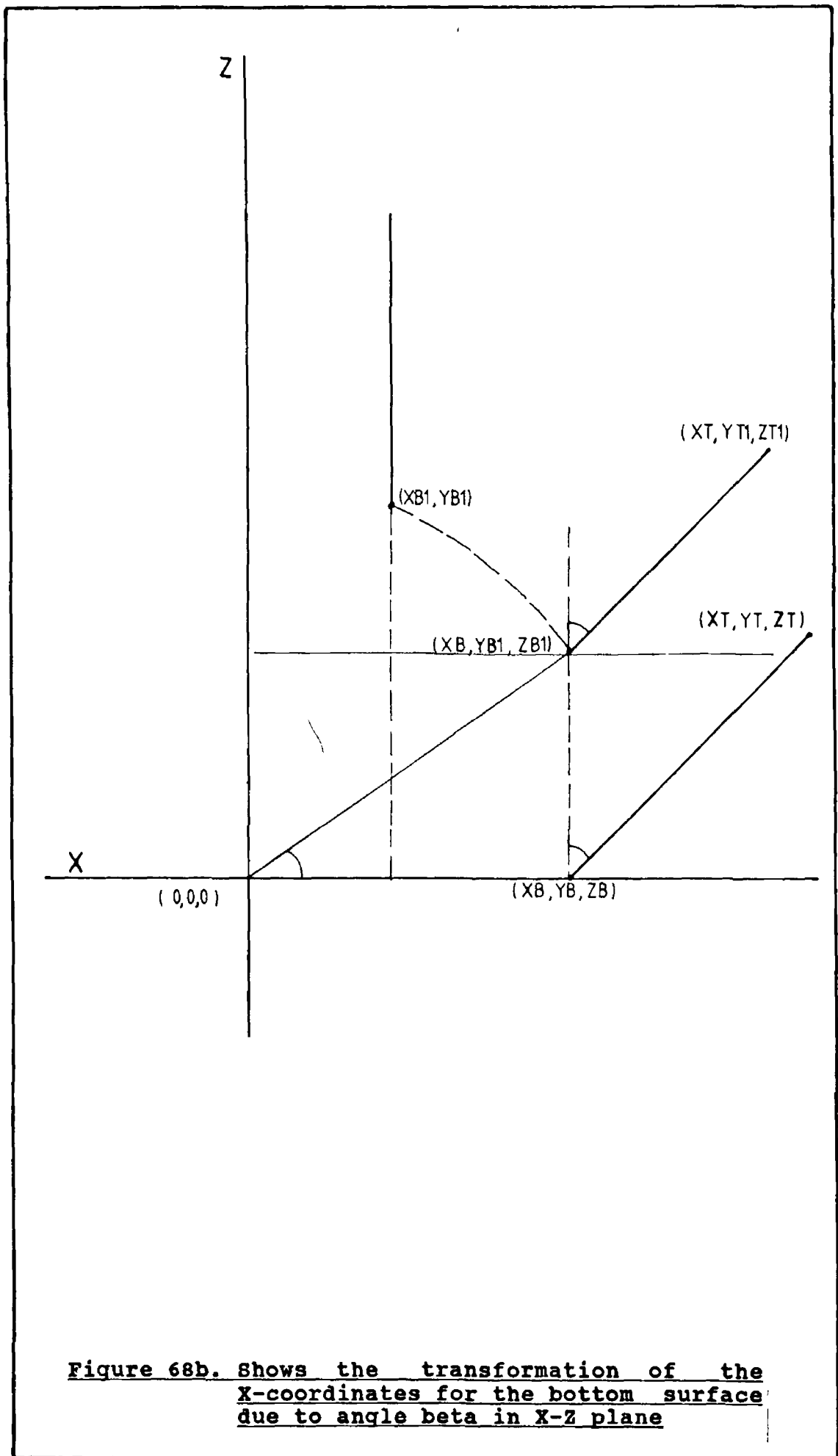
Figure 68b. Shows the transformation of the X-coordinates for the bottom surface due to angle beta in X-Z plane
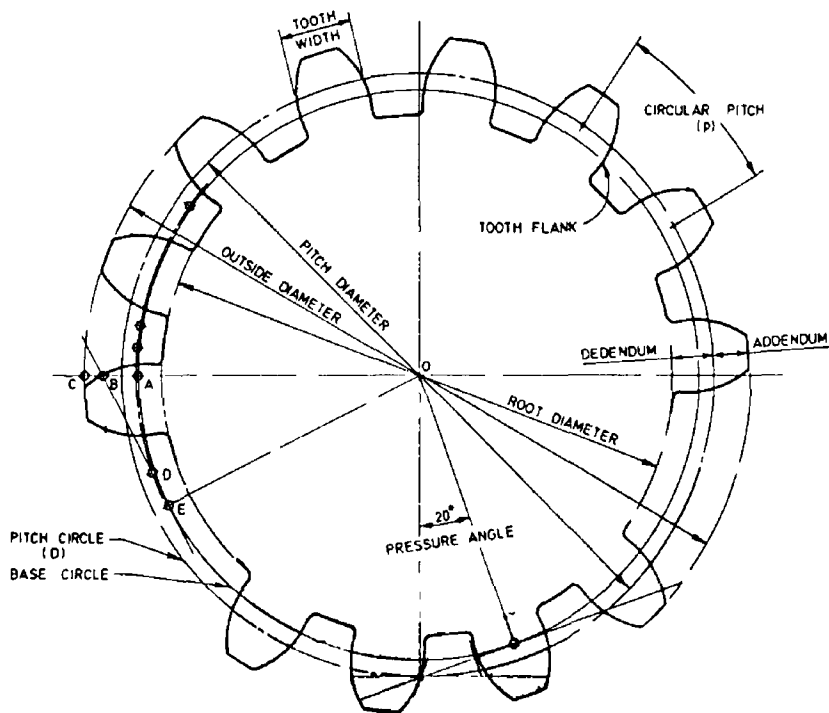
Figure 69. Shows the geometric construction for the spur gear
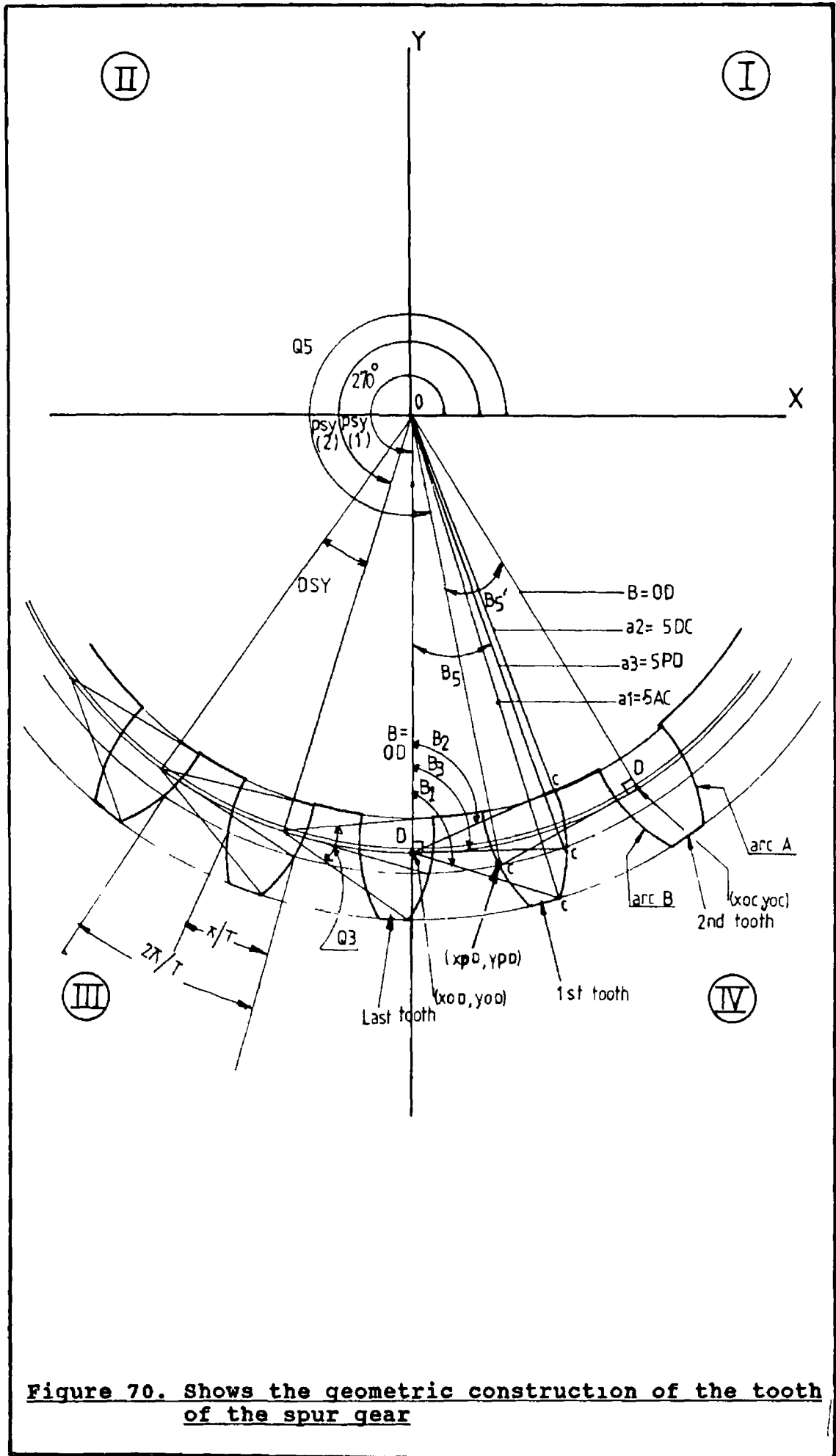
Figure 70. Shows the geometric construction of the tooth of the spur gear
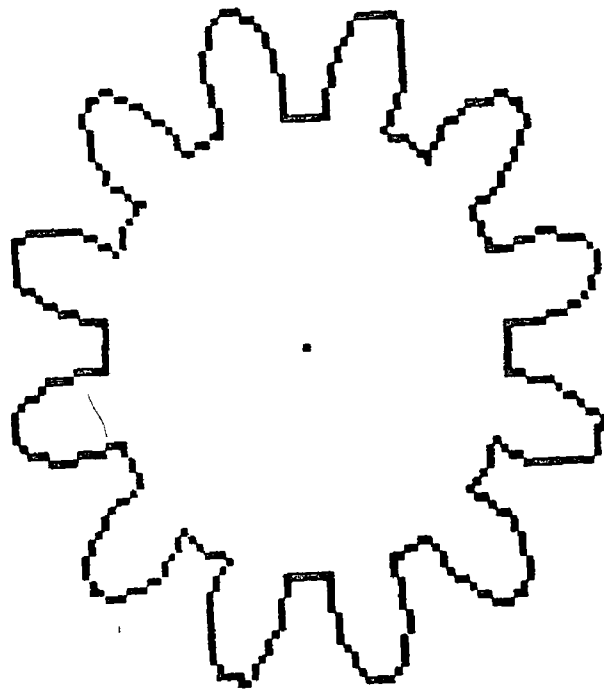
Figure 71. A print out of the graphical drawing of spur gear generated by the computer
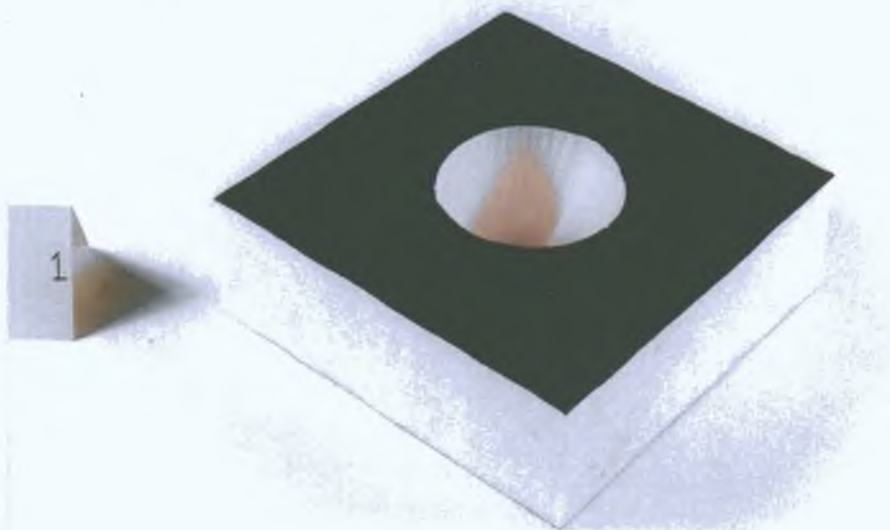
TOP SURFACE
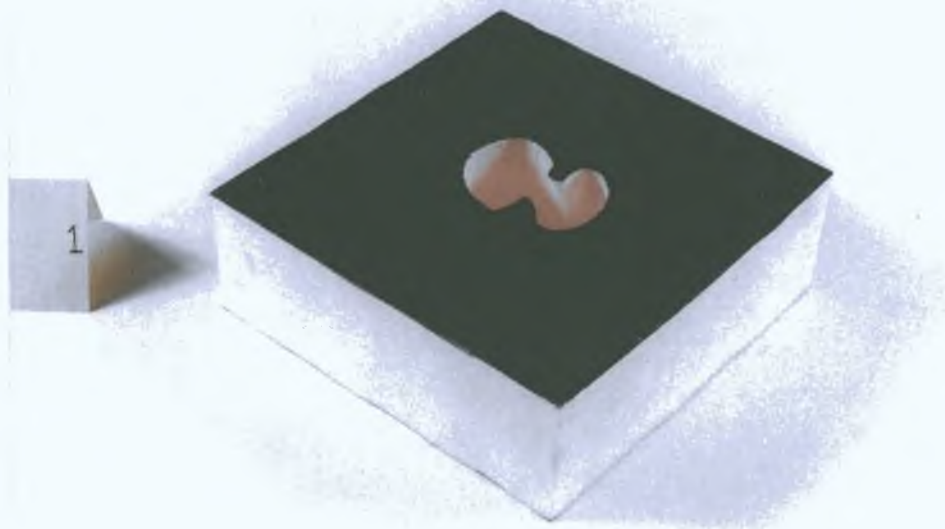
BOTTOM SURFACE

PLATE 4. CIRCLE TO COMPLEX
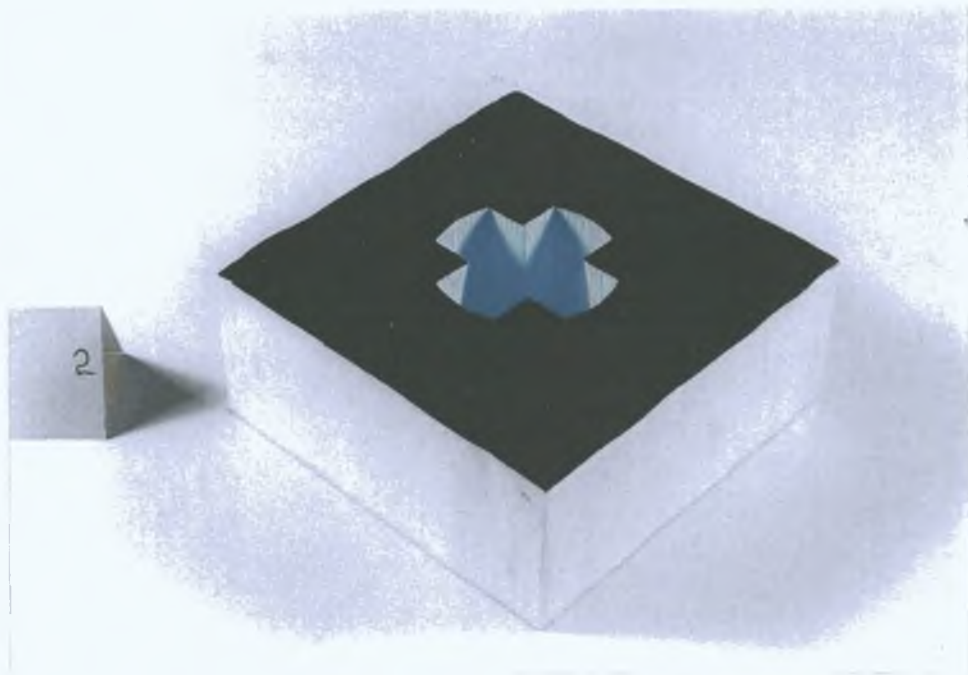
TOP SURFACE
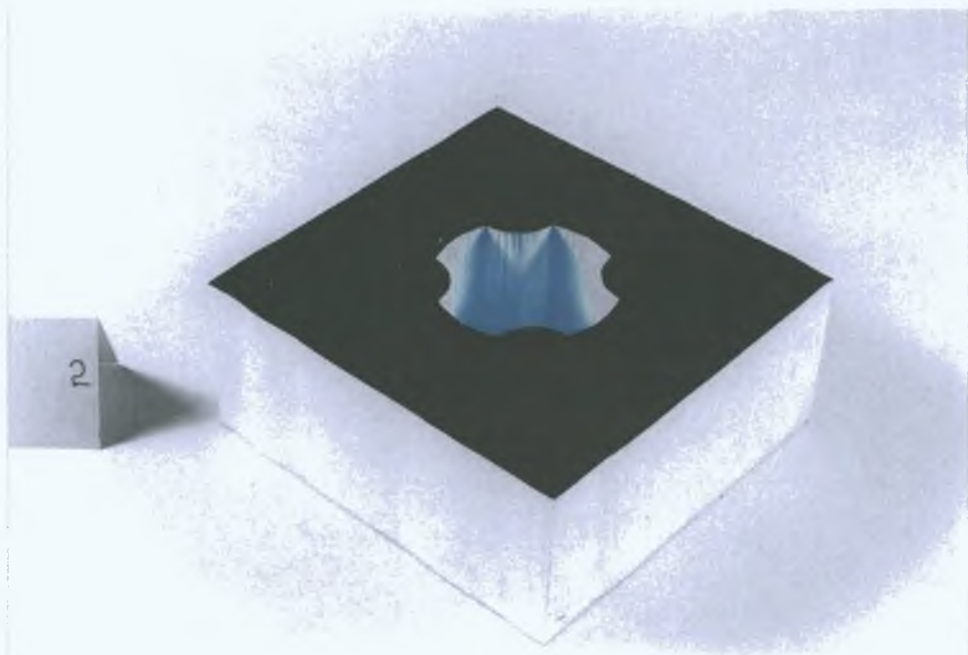
BOTTOM SURFACE

PLATE 5. STRAIGHT SIDE CROSS TO

CURVED SIDE CROSS

PLATE 6.   A SPUR GEAR

CHAPTER FIVE

RESULTS AND DISCUSSION

5.1. INTRODUCTION

The precision manipulator, which is basically a purpose built robotic end-effector to be used for controlling the motion of a specimen in such a way that 2-D/3-D complex shaped surfaces may be generated using simulated WEDM process on model material (polystyrene) where the cutting forces are relatively negligible. The design criteria of the manipulator was based on mainly two factors, firstly, the manipulator should have more angular cutting facility with least possible number of axes to be controlled at lowest power and motor torques and secondly, it should be independent of the WEDM/ECM machines and be cheaper to purchase separately than buying fully integrated with CNC WEDM/ECM systems.

The interfacing system chosen is an appropriate system for this particular application, which contains very basic and important control parameters, execution, status request and general purpose commands. The command construction and flexibility of the interfacing system which is detailed in chapter three, is very compatable with the known programming languages ie. "BASIC", "C" and "PASCAL". Therefore, the programming language for

describing the geometry of the shapes can also be used to carry out the functions by using the special purpose PC23 indexer commands. The software described in chapter four are designed in such a way so that the optimum results can be achieved by the precision manipulator/interfacing system.

The investigation of the effectiveness of the precision manipulator/software was done in terms of:

(a)   the accuracy of the geometrical shapes generated

(b)   quality of the machined surface by varying the

    (i)   shape of the surface,

    (ii)   size of the specimen/shape generated and

    (iii)   speed of the process.

The present design of the manipulator is not suitable for carrying out tests on the real WEDM machine, since the workpiece needs to be immersed into dielectric fluid. The simulated WEDM process was carried out by using a hot wire and a model material in place of the WEDM machine and tool steel material respectively.

The initial tests were carried out on a very low density and poor quality of polystyrene. Using this material the investigation of the accuracy of the shape and quality of the surface were very difficult to study. This low density material showed very little difference for

different cutting speeds and voltages supplied to the cutting wire. Therefore, the decision was made to change the model material. Subsequently, all the tests were carried out on different kinds of extruded polystyrene, which has the density of 34 kg/m^3 and compressive strength of 300 KN/m^2 and fairly good surface quality.

Using this new material it was possible to as certain differences in the shapes generated by supplying different voltages to the cutting wire at different workpiece feedrates. The best shape accuracy and surface quality can be achieved at 5.5 volts and at 500 mm^2/min to 800 mm^2/min workpiece feedrate. Therefore, the voltage supplied for all the other shapes generated was kept at 5 5 volts.

In total eight software were developed from which 12 different 3-D shapes were generated. All these 3-D shapes were generated in 49 mm thick workpieces. One software for 2-D shape (spur gear) was also developed and different sizes of spur gears were generated. The size of all the 2-D/3-D shapes is user selected at different workpiece thicknesses. The results achieved from all of the 2-D/3-D shapes are described in the following sections.

5.2. RESULTS

5.2.1. RESULTS FOR CIRCLE TO COMPLEX SHAPE GENERATION

For generation of circle to complex 3-D shape, one

hundred points were chosen for each surface. As the machining was started from the centre "home" position and returned to the home position at the end of the full die generation, therefore, the home position at start and end position were counted as two more points to be programmed. As it is described in section 4.3.2 that the complex shape is the formation of twenty arcs of different sizes, the number of points for generating circle to complex shape are kept 60, 80, 100 or 120 according to user's choice. Due to the limitation of the computer memory the maximum number of points which could be used is about 120.

By choosing one hundred points every single arc of the complex shape was divided into 4 small segments. Therefore, the arcs of the bigger sizes produced fairly good curvature at five number of points (4 segments), when the radius is magnified to about 20 mm. Thus the radius of the circle was chosen as 25 mm. The geometric description for the circle to complex shape is detailed in topic 4.3. The photograph of the circle to complex shape generated in a 49 mm thick model material is shown in plate 7.

The wire cutting path on the die profile was measured to be approximately 0.5 mm wide. If the locations of the points on the profile were very close (ie smaller segments), then the wire cutting path was observed to be slightly bigger than 0.5 mm for either of the surfaces. The reason for this was observed to be the presence of the power in the cutting wire during the pause when the data

communication between the computer and the PC23 indexer takes place for the generation of each smaller segment.

This overcut can be avoided by theoretically predicting the delay time between two segments and then during that time the power supplied to the cutting wire can be reduced. The other way of avoiding this overcut due to cutting wire diameter can easily be compensated through software. The desired and achieved profiles for circle to complex shapes are shown in figure 72.

The total machining area for this die cavity of 19456.3 mm^2 was eroded in 28 minutes and 24.9 seconds (practical machining time) at the chosen workpiece feedrate of 600 mm^2/min. The theoretical machining time estimated for this shape was 15 minutes and 45.62 seconds. The machining data and the machining conditions chosen for the specimen plate 7 are given in figure 72. From this data the time difference of 12 minutes and 39.28 seconds, is the delay time for generating the die cavity. During the machining process, it was observed that after the generation of each segment the motor motions were paused for a few seconds before the next segment generation. This pause was observed to be the time taken for communication between the PC23 indexers and the micro-computer. It has been checked that these pauses add up to the difference between the theoretically estimated and experimentally observed machining time.

5.2.2. RESULTS FOR SQUARE TO COMPLEX SHAPE

The square to complex shape was generated by using a fixed number of 80 points for each surface. The data for the square shape were fed into the program at a unit scale of one mm. Bigger sizes of both the surfaces can be achieved for user selected magnification.

The size of the square chosen was 50 mm x 50 mm (ie magnification of 25). Where each side of the square is represented by different number of points. The reason for that is to match the location of points of the complex shape at the bottom surface. The magnification chosen for the complex shape at the bottom surface is 20. The software developed for the square to complex shape is given in Appendix C5. The die cavity generated for the square to complex shape is shown in plate 8.

The width of the wire cutting path on both the surfaces was found to be fairly constant at approximately 0.5 mm. The desired and achieved profiles for the circle to complex shape are compared in figure 73.

The total machining area of 10506.55 mm^2 for the square to complex shape was machined in approximately 28 minutes (practical machining time) at the workpiece feedrate of 500 mm^2/min. The theoretical machining time calculated to generate this die cavity was 21 minutes. The difference between the theoretical and practical machining

time for the die cavity is approximately 7 minutes. The machining data and machining conditions for the square to complex shape are given in figure 73.

5.2.3. RESULTS FOR CIRCLE/PRISMATIC TO CIRCLE/PRISMATIC SHAPES

The software developed for circle/prismatic to circle/prismatic shapes is described in topic 4.6, and the software is given in Appendix C4. This software allows to generate square, rectangle or circle shapes at either of the surfaces for user selected number of points, sizes and workpiece thickness. Five different 3-D shapes were generated by making use of this software, circle to circle, square to square, circle to square, square to circle and a strip drawing die. The circle is divided into equal lengths of user selected number of arcs. Each side of the rectangle is also divided into equal number of points. The first four shapes were generated by selecting 80 points on each surface. For the strip drawing die 40 points were chosen.

The photograph of the circle to circle shape generated is shown in plate 9. The radii for the top and bottom chosen surfaces were 25 mm and 20 mm respectively. The machining area of 9130.43 mm^2 for the circle to circle die cavity was machined in approximately total time practical machining time of 19 minutes and 24.8 seconds at the selected workpiece feedrate of 800 mm^2/min. The desired

and achieved profiles for the circle to circle shape are shown in figure 74. The theoretical machining time calculated to generate the circle to circle die cavity was 11 minutes and 24.78 seconds. The difference between the practical and theoretically calculated machining time observed was approximately 8 minutes. The wire cutting path for the circle to circle shape was seen to have a regular width of 0.5 mm

Plate 10 shows the photograph of square to square shape on a 49 mm thick workpiece. The square for the top surface was chosen to be of 50 mm x 50 mm and for the bottom surface of 30 mm x 30 mm size. The total area of 10611.86 mm^2 for this die cavity was eroded in 19 minutes and 57.37 seconds (practical machining time) at a workpiece feedrate of 800 mm^2/min. Figure 75 shows the desired and achieved profile for the square to square shape. The machining data and machining conditions for this die cavity are also given in figure 75. The calculated theoretical machining time for this die was 13 minutes and 15.88 seconds. The difference in the theoretical calculated and practical machining time was observed to be 6 minutes and 41.5 seconds as shown in figure 75.

The photograph of the circle to square shape is shown in plate 11. The radius for the circle at the top surface was chosen to be 25 mm and a square at the bottom surface was selected to be of the size of 30 mm x 30 mm. The total machining area of this die cavity of 9051.91 mm^2 was

machined in total practical machining time of 20 minutes and 30.6 seconds at a workpiece feedrate of 800 mm^2/min. The desired and achieved die profiles for the circle to square shape are shown in figure 76. The calculated theoritical machining time for this die cavity was 11 minutes and 18.9 seconds. The difference between the theoretical and practical machining time was approximately 9 minutes and 11.8 seconds. The machining data and machining conditions for the circle to square shape are given in figure 76 as well.

The square to circle shapes generated in the 49 mm thick workpiece is shown in plate 12. The square shape at the top surface was selected to be of the size of 50 mm x 50 mm and the radius for the bottom surface was chosen to be 25 mm. The total machining area for the square to circle shape of 11704.88 mm^2 was machined in 22 minutes and 17.12 seconds at a workpiece feedrate of 800 mm^2/min. The desired and achieved die profiles for the square to circle shapes are shown in figure 77. The machining data and selected machining conditions for the square to circle shape are also given in figure 77. The theoretical machining time for this die cavity was calculated to be 14 minutes and 37.86 seconds. Therefore, the difference in the practical and theoretical machining time for this die is equal to 7 minutes and 39.3 seconds.

The strip drawing die was generated by selecting a larger rectangular shape of 60 mm x 20 mm at the top the

surface and a smaller rectangular shape of 20 mm x 4 mm at the bottom surface. The photographs of the top and bottom surfaces generated for the strip drawing die are shown in plate 17. Plate 18 shows the photograph of the plan view of the same die cavity.

The total machining area for the strip drawing die of 7145.72 mm^2 was machined in 17 minutes and 16.26 seconds at the machining rate of 500 mm^2/min. The width of the wire cutting path at the top surface was found to be of 0.5 mm. The bottom surface profile is much smaller than the top surface profile, where as the number of points on both the surfaces is the same ie. 40, and the power in the cutting wire remains the same to erode both the top and bottom surface profiles. Therefore, more time was available to erode material at the bottom surface than at the top surface. For this reason the width of the wire cutting path at the bottom surface was observed to be slightly greater than at the top surface. The desired and achieved die profiles for the top and bottom surfaces are shown in figure 82. The machining data and machining conditions chosen for the strip drawing die are also given in figure 82. The theoretical and practical machining difference between time for the strip drawing die to be machined was approximately 2 minutes and 58.9 seconds.

5.2.4. RESULTS FOR SQUARE TO SQUARE SHAPE AT 90°s ROTATION

For the generation of square to square shape at 90°

rotation the data was fed in within the software at unit scale of one mm for 80 fixed points. The size of both the surfaces can be selected as required within the machining capability of the manipulator. Two sets of die cavities of different sizes for the square to square surface at 90° rotation were generated using the same software.

The photograph of the larger square to square die cavities generated is shown in plate 13. The top surface square was selected to be 50 mm x 50 mm and the bottom surface square magnification chosen as 25 giving the size of 35.35 mm x 35.35 mm. The machining area of 10814.82 mm^2 was machined in total machining time of 22 minutes and 58.6 seconds at a workpiece feedrate of 600 mm^2/min. The desired and generated square profiles at 90° of rotation are shown in figure 78. The machining data and machining conditions chosen for this die cavity are also given in figure 78. The difference between the calculated theoretical and practical time for this die cavity was 4 minutes and 57.1 seconds.

Plate 14 shows a photograph of the smaller size of the square to square shape generated. The size for the square at the top surface was 50 mm x 50 mm and the bottom surface square size selected was 14.14 mm x 14.14 mm. The desired and achieved profiles for this die cavity are given in figure 79. The machining data and machining conditions for this die cavity are also given in figure 79.

The total area for this die cavity of 8000.936 mm^2 was machined in a practical time of 15 minutes and 14.5 seconds at a workpiece feedrate of 800 mm^2/min.

The desired and achieved profiles for the top and bottom surface squares are shown in figure 79. The machining data and machining conditions for this die cavity are also given in figure 79. The difference between the theoretical and practical machining time for this die was observed to be 5 minutes and 7.5 seconds.

5.2.5.   RESULTS FOR CIRCLE TO STAR SHAPE

For generating the circle to star shape, a fixed number of 80 data points was chosen. The data of 80 points representing the star shape was fed in the program at unit scale of one mm, where the same number of data representing the circle shape was calculated by the program.

The radius for the circle shape was selected to be 30 mm and the magnification chosen for the star shape was 30 as well. Plate 15 shows the photographs of the circle to star shape. The total machining area for the circle to star shape of 12915.17 mm^2 was machined in approximately 21 minutes and 15.9 seconds at a workpiece feedrate of 800 mm^2/min. The desired and achieved profile for the circle and star is shown in figure 80. The machining data and machining conditions for this die cavity are given in figure 80 as well. The difference between the calculated

theoretical and practical machining time was noticed to be approximately 5 minutes and 7.27 seconds.

5.2.6. RESULTS FOR CIRCLE TO CRESENT SHAPE

The software describing the circle to cresent shape is detailed in topic 4.5. This 3-D shape was generated by choosing 60 points on each surface.

The radii selected for the circle shape and the outer edge of the crescent shape were 20 mm and 15 mm respectively. The photograph of the shape generated for the circle' to crescent is shown in plate 16. The total machining area for this shape of 7609.85 mm^2 was machined in 15 minutes and 47.76 seconds at a workpiece feedrate of 800 mm^2/min.

The desired and achieved profiles for the circle to crescent shape are shown in figure 81. The machining data and machining conditions for this shape are also given in figure 81. The difference between the calculated theoretical and practical machining time for the circle to crescent shape was found to be approximately 6 minutes and 17.37 seconds.

5.2.7. RESULTS FOR A CIRCULAR TAPERED DIE

The software describing the technical geometry of the circular tapered die is detailed in topic 4.4. This die is

generated in three stages. The generation of each stage is described by a circle at the top and bottom surfaces by 60 points. In the first stage two circles at both the surfaces were manufactured having the same radii of 3.5 mm to form a straight circular hole.

The second and third stages were formed by describing two circles of different sizes at both the surfaces. The points representing the bottom surface circles were out of phase by 180° with respect to the corresponding points representing the top surface circles for both these stages. In the second stage the radii for the top and bottom surfaces were decided to be of 15 mm and 2 mm respectively.

The radii for the top and bottom circles in the third stage were seen to be more suitable to form the circular tapered die at the values of 18 mm and 10 mm respectively. The photograph of the circular tapered die generated is shown in plate 19.

The machining area of 1420.1 mm^2 was eroded in 13 minutes and 18.8 seconds (practical machining time) at the workpiece feedrate of 400 mm^2/min for stage one. The difference between the practical and theoretical machining time for stage one was approximately 9 minutes and 45.9 seconds. For calculating the machining area for the second and third stages, attention has to be paid to the areas already machined away in the first and second stages respectively which are being accounted for during stage two

and three at the intermediate cross-section of the die cavity. However, this double accounting of areas in second and third stages was left uncorrected in order to avoid the complexity in the programming and also to minimise the burden on the CPU and affect the program execution speed. Also the main concern here is to simulate the WEDM process with more cutting flexibility of the manipulator. Figure 83 shows the cross sectional profiles desired and achieved after each of the three stages. The machining data and machining conditions for all three stages are also given in figure 83.

By carefully observing the plate 19 which shows the vertical cross-section photograph of both halves of the generated die, it can be seen that the profiles on both halves are not exactly regular and symetric.

The reason for this is attributed to the type of material used and the three stages of the machining. After generating the first stage, when the second and third stages were generated, the material already eroded away in the first stage and second stage produced a thin layer of melted material on the cavity surface. In the second and third stage generation, this layer of the melted material at crossing sections of the different stages caused the unsymetric vertical cross-section of the die profile. In particular, during the generation of, third stage the melted layer of the material (more dense) was seen to be difficult to machine than the other unmelted material of

the die and at some occasions it was also observed that this melted material was stuck with the cutting wire.

5.2.8. RESULTS FOR SPUR GEAR GENERATION

The software developed for generating the spur gear is explained in topic 4.12 and is given in appendix C10. Using this software a pinion and a wheel gear were generated. Plate number 20 shows the pinion and the gear sheel in mesh having the same module of 5. The pitch circle diameter and pressure angle for the pinion were selected to be 60 mm and 20 degrees respectively. Points were chosen on each arc of the teeth of the pinion gear. In total 250 points were calculated for the twelve teeth of the pinion gear to be generated. To generate this pinion gear total machining area of 13906.8 mm^2 was machined in 40 minutes and 53 seconds (practical machining time) at the workpiece (30 mm thick) feedrate of 500 mm^2/min. The desired and achieved pinion gear profiles are shown in figure 84. The difference between the calculated machining time (theoretical) and practical time is 13 minutes and 4.2 seconds as given in figure 84.

The pitch circle diameter and pressure angle for the gear wheel were selected to be 80 mm and 20 degrees respectively. Five points were chosen on each tooth arc for the gear wheel. In total 302 points were calculated for the gear wheel for 16 teeth to be generated. For this gear wheel the total machining area of 17208.24 mm^2 was

machined in 45 minutes and 12.7 seconds (practical machining time) at workpiece feedrate of 600 mm^2/min. The desired and achieved gear wheel profiles are shown in figure 85. The machining data and machining conditions for the gear wheel are also shown in figure 85. The difference in the theoretical and practical machining time was found to be approximately 16 minutes and 31.88 seconds.

5.3. DISCUSSION

Feasibility studies suggested that the linear and angular manipulation of the workpiece movements were more suitable to achieve precise 2-D/3-D complex shapes using WEDM process. A minimum of four degrees of freedom (two linear and two rotary) were sufficient to achieve 3-D complex shapes.

Therefore a four axes precision manipulator was designed to carry out the tests for non-traditional methods of machining in which the metal removal forces are negligible, in particular for WEDM process. One of the aims of this research was to design a low cost precision manipulator, that could easily be used in conjunction with existing WEDM machines to produce precise 3-D complex shapes with more angular cutting facility and less programming efforts than offered by very expensive WEDM machines which are currently available. The present design of the manipulator is not suitable for carrying out tests on real WEDM machines and real material and in order to use

the manipulator on a real WEDM machine, the motors need to be sealed from splashes of the dielectric fluid.

The design of the manipulator was decided to be in such away so that only the workpiece housing part (inner and outer frames) of the manipulator remains in the working area and rest of the manipulator body is kept out of the working vicinity. In this way, the maximum angular cutting facility can be achieved without interference from other mechanical parts. Only the cutting wire remains in touch with the workpiece and the wire cutting unit (drawing number 01A) permitted to carry out all the linear and angular movements by the precision manipulator. The motor number one for X-axis linear movement was observed to be noiser than the rest of the other motors. The reason for this was observed to be the misalignment of the lead screw with the X-axis manoeuvring unit (drawing no. 01D01) which means the lead screw was not being in perfectly straight position.

In general, the responsiveness of the manipulator was observed to be very satisfactory in terms of the commanded manipulation, which generated the 2-D/3-D shapes. All the 2-D/3-D shapes were generated according to their geometry description with greater flexibility and no problem was observed related to operation of the manipulator. However, on some occasions, the cutting wire was seen to be attached to the workpiece at the first retracing point. The cutting wire was then detached by applying a little force by the

finger. This was probably the result of melted workpiece material and as soon as the voltage to the cutting wire was stopped after the trigger input signal was encountered it remained attached with workpiece melted material. If at the start of shape generation, the voltage value selected was higher, then the cutting wire did not get attached to the workpiece at the first point of retracing. It means that the present power in the cutting wire was more than the workpiece feedrate which caused more material to be eroded away by the cutting wire and the cutting wire remained detached from the workpiece.

5.3.1. EFFECTIVENESS OF THE INTERFACING SYSTEM, IT'S COMMANDS AND OF THE PVR CIRCUIT

The interfacing system used in this research work was commercially bought and is of multiple purpose. The information supplied with the interfacing system was contradictory, confusing and disorganised. The problems encountered during interfacing and with PC23 commands have been described at the end of chapters three and four. After overcoming these problems related to the interfacing system and its commands, the responsiveness of the interfacing system was seen to be quite stable.

The facilities offered by the interfacing system of installing optional encoder, CW and CCW limits switches and home positioning switch were not utilized in the present

research work.

One of the main encoder functions for position maintenance was solved by programming the motor number three for compensation of 1° of backlash. However, it does not rectify any error due to the slackness of other parts of the manipulator. Other position tracking functions beside the compensation for the backlash of the encoder are also very important, if the manipulator is going to be used on a read WEDM machine. These functions which can be achieved by using PC23 indexer encoder commands are;

(ı)   Dynamically holding the encoder position by applying increased resistance to external forces.

(II)   Independently verifying the load postion.

(ııı)   Detecting the motor stall position.

The function of CW and CCW limit switches is to protect the over travel, which might cause damage to the manipulator/workpiece or motors etc. However, by knowing the working space of the manipulator the maximum travel limits for all the axes are known. Therefore, the problem of linear and rotary over limit travel was solved through the software. There is no absolute assurance of avoiding over travel, which might occur because of programming mistake. For avoiding these kind of mistakes a number of tests were carried out without any workpiece on the manipulator to make sure that there will be no such error

which might cause any damage to the hardware.

The function of the home position switch is to establish a home position from which the future corresponding axes movements will be commanded with respect to this home (zero) position. For the manipulator being discussed here the suitable home position of the switch to be installed is the centre of linear travels and for rotary movements the parallel position of the manipulator frames with respect to its base.

For generating 3-D shapes, all the co-ordinates on the die profile are known and the centre co-ordinates (home) of the workpiece are known as well. Therefore, by knowing all these co-ordinates and using absolute operating mode of the PC23 indexer the home position was established by the software. The workpiece centre position was treated as the initial wire position (home - position) and at the end of 3-D shape generation the wire was also programmed to be at the home position. The software response to the CW and CCW limit switches for backlash compensation of the home reference position, were observed to be very promising for further developments.

The trigger input signal and programmable outputs are logical extension to the adaptive control as an integrated part of the CNC system. The hardware circuitry and software switches were designed to test these facilities offered by the interfacing system as explained in chapter

three. The responsiveness of these facilities was observed to be very satisfactory.

The response of the PVR circuit for the control of the voltage in the cutting wire was also observed to be very satisfactory. On some occasions, the selected voltage was found to vary from the selected level, opening the PVR circuit the corresponding potentiometer was adjusted to achieve the desired voltage and current values. This was due to some fault with the potentiometers, which can be solved by replacing these potentiometers by new ones.

5.3.2. THE EFFECTIVENESS OF THE MICRO-COMPUTER AND SOFTWARE DEVELOPED

The calculations for geometry description, the path planning and for controlling the motion of the 4 axis manipulator for the simulated WEDM process are carried out by the same micro-computer. The computer used is an IBM compatible with 640k RAM. The programming language used is BASIC.

The EDM process is known to be slow but very popular and effective amongst all the non-traditional methods of machining. Each 2-D/3-D shape was described by calculating a number of points for the shape profile. Therefore, for each segment to be generated it is necessary to have all the conditions specified for each point in a synchronized manner. It means that a large memory is required to store

all these pre-calculated move parameters for each point.

All the 2-D/3-D shape generating programmes are divided into two parts, the first part describes the shape geometry and the second part plans the machining path, sets machining conditions and controls the 4 axes manipulator. In the second part, which generates each segment, there is a string variable containing the PC23 character commands and their corresponding values for all four axes. The "Output Driver" can send only one command character at a time. Controlling four axes means communicating with two PC23 indexers at their different base addresses.

If the theoretical machining time required for any segment to be generated was more than 12 seconds then at the end of the move the process had a minimum of around 2 seconds pause before the next move started. This pause was noticed to have increased to about 10 seconds if the minimum segment generation time was around 2 seconds. The lengths of the control commands sent to the PC23 indexers was nearly the same for all the points. Therefore, if the machining time for any segment to be generated is longer, then in the mean time the current segment was being generated the process of control commands sent to the PC23 indexers was completed and it took less pause time for the next segment to be generated and vice versa. The greater the pause time between two segments, the greater the inaccuracy in the die profile.

Checking the trigger input signal means to get the response back from the PC23 indexer one. For adaptive control optimization, a number of different parameters are continuously monitored (ie reading trigger input signals) and the appropriate conditions related to the parameters are set (ie setting programmable outputs). Monitoring more than one condition means getting a number of responses back from the PC23 indexers which need more communication time. Therefore, it will cause more pause time and will affect the overall efficiency and performance of the system.

The size of the programs, number of variables and controlling each axes in a real time makes the process inefficient and well beyond the real time control speed. Therefore, a faster computer with large RAM is of basic importance to control the process in real time. For using the manipulator on a real WEDM machine it may also require changing of the programming language to other compiled version of the programming language.

Besides this time delay, the responsiveness of the software developed was observed to be very satisfactory and encouraging. The shapes generated were quite in accordance to what they were intended. The machining time in synchronized manner was measured to be perfectly as it was calculated, except the pause time between the two segments was seen to be changing with respect to the machining time, which is totally unnecessary and will not allow carrying out tests on the real WEDM process. If the points are too

close to each other then the linear and angular differences between the two splines are too small and the computer calculated format can give an error of up to sixth or seventh decimal digit which might affect further calculations and can cause minor inaccuracy in the expected movements.

5.3.3. EFFECT OF THE SHAPE DIFFERENCE ON THE 3-D DIE CAVITY

The main idea of this research was to produce 3-D shapes in a block of material having drastically different shapes on two of its faces. Therefore, a number of different 3-D shapes were generated and studied.

All the 3-D shapes generated can be classified into two categories. The 3-D shapes in the first category, were those shapes which were described in such a manner so that the corresponding connected points between the top and bottom surfaces were at the same angular location in their own cartesion co-ordinate system. These shapes were found to be in accordance with their shape geometry description. The splines making slopes between the top and bottom faces did not overlap the intermediate section. Therefore the resulting die cavities and surfaces generated were very satisfactory. An overcut of approximately 0.25 mm was observed, which was caused by the wire diameter and the current passing through the cutting wire.

The 3-D shapes in the second category were those

shapes in which the location of points on both the surfaces were not equidistance. The examples of these shapes are circle to complex shape, square to complex shape, and circle to crescent shape. The top surface geometry was described in comparison to the bottom surface geometry description. If the required outlet die cavity was complex and the inlet geometry required was circle, then the top surfaces was described in such a way that the intermediate surfaces should not overlap the bottom shape geometry. Therefore, the location of the points for the top surface needed to be changed The points described for the circle shape were chosen at some places and at other places they were located at some distance from each other. The overcut was found to be greater for the shapes where the points were quite close to each other than when the points were not so close to each other. None of the intermediate surfaces observed to be overlapping the bottom surface in all the 3-D shapes which were generated.

5.3.4. THE EFFECT OF THE SPEED, VOLTAGE LEVEL, NUMBER OF POINTS AND SIZE OF THE SHAPE ON THE ACCURACY, SURFACE QUALITY AND REPEATABILITY

All the 3-D shapes can be generated by the user selected magnification within the capability of the manipulator. The geometry of only three shapes was described by 80 points. The square to complex, square to square at 90° of rotation, and circle to star, all the other shapes can be described by user selected number of

points. For all the shapes generated, the workpiece feedrate and voltage supplied to the cutting wire is also user selected.

The effect on the accuracy of the shape and on the surface quality is mainly governed by the speed and voltage levels. The number of points was also observed to have an effect on the profile of the shape and surface quality. The size of the shape seemed to have the effect on the accuracy of the shape due mainly to the speed (workpiece feedrate). The effect of the speed, voltage and number of points on the accuracy and surface quality is dependent for the shapes of category one and two, as classified in previous section.

For the shapes of both the categories, higher number of points and higher process speed means lower machining time between two consecutive points at the top and bottom surfaces. If the voltage level selected was 4.5 volts or less and the micro switch was not housed on the wire cutting unit then the wire cutting rate was observed to be less than the workpiece feedrate, and if any corner was intended to be generated for the die cavity, then the generated shape was, observed to have an arc shape instead of corner. Under same machining conditions, if the voltage supplied to the cutting wire was 5 volts or greater, the pause time (as detailed in topic "Effectiveness of the micro-computer and software developed") caused more material to be eroded away from the

die cavity at all the splines connecting the top and bottom profile points. This phenomenon caused inaccuracy and relatively poor surface quality.

For all the shapes of category one all the points on the circles and on the sides of the prismatic shapes are equidistant for lower number of points and for lower speeds. If the machining time for each segment was calculated to be 12 or more seconds with respect to the workpiece feedrate and selected size (magnification) and the voltage supplied to the cutting wire was approximately 5.5 volts, the shape generated had good surface quality and accuracy of the die cavity. Once the voltage level was established with respect to the workpiece speed and the machining time was at least 12 seconds, then the higher number of points resulted in very good accuracy and surface finish. The machining time of at least 12 seconds is for the machining area, which covers the size of the workpiece. With the above parameter values the minimum pause time between two segments to be generated was noticed to be around 2 to 3 seconds. During this time the hot wire erodes very little material from the workpiece and produced slightly curvy shapes on the die cavity, which is actually spline between top and bottom surface. This can easily be seen in the photograph.

For the shapes of category two, in which all the points on both the surfaces are not equidistant because of the complexity of the bottom surface, the situation

changes. As the points are not equidistant, therefore, the machining time changes at different places for different segments to be generated. At the voltage of 5.5 volts on the die cavity where the points were very close to each other the surface was observed to be quite fine and smooth finish, but with more material eroded (ie. wire cutting path slightly more than 0.5mm wide) and less accuracy of the size. At other places where the points were located at a slightly more distance from each other, die profile accuracy and surface quality were observed to be similar to those for the shapes described for the first category.

Plate 21 shows the photograph of the square to complex shape of different sizes having the same number of points and different feedrates. Figure 86 shows the desired and achieved shape profiles. Figure 86 also shows the data and machining conditions selected for the square to complex shape. Plate 22 shows the photograph of the straight sided cross to curved sided cross shapes generated for the same size but at different speeds. Figure 87 shows the desired and achieved shape profiles for plate 22. The same figure also shows the data and machining conditions for the straight sided cross to curved sided cross shape.

As the minimum points on all the 3-D shapes generated were chosen to be 80 except for the strip drawing die shape, therefore, it produced fairly acceptable 3-D shapes. The repeatability for all the 3-D shapes generated under similar conditions was found to be very good.
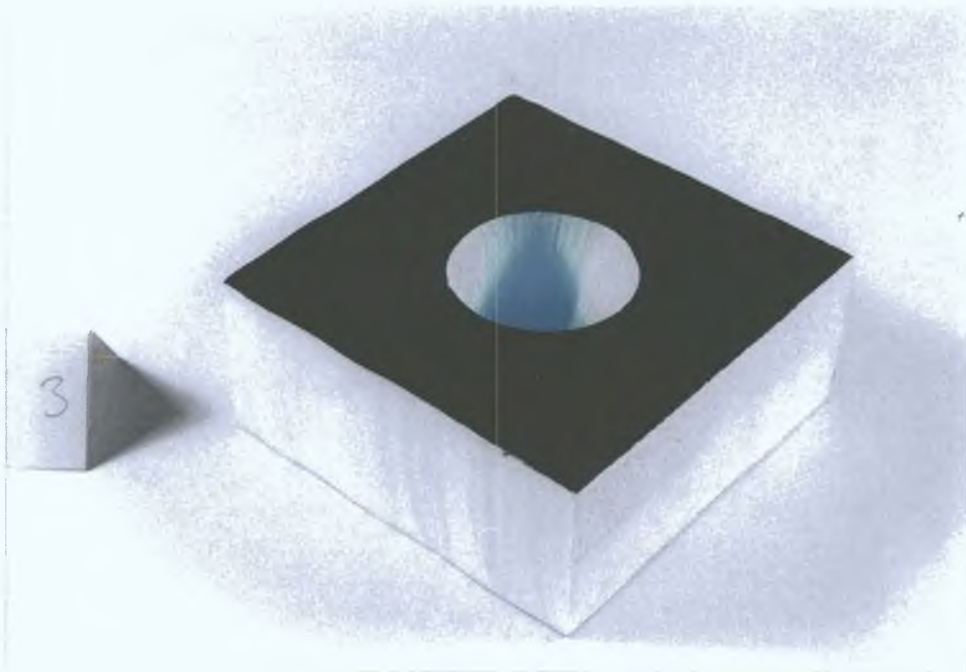
TOP SURFACE
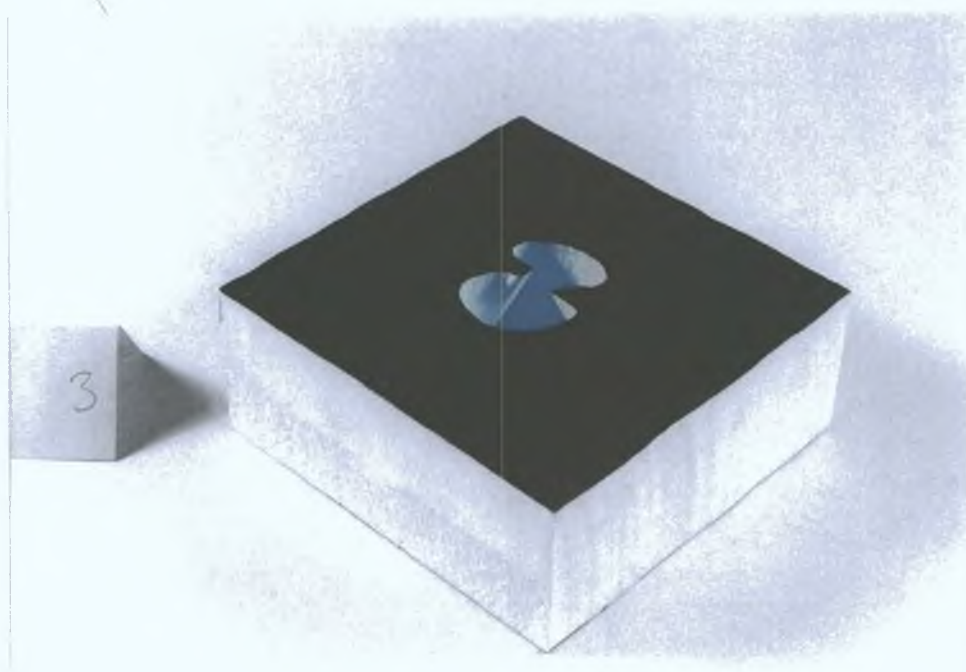
BOTTOM SURFACE

PLATE 7. CIRCLE TO COMPLEX

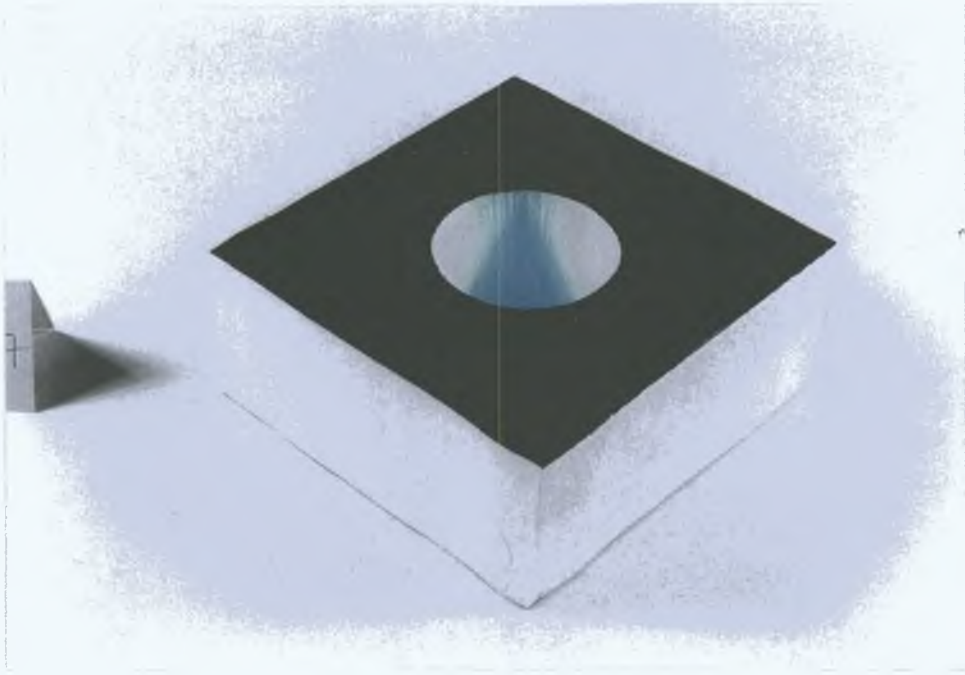TOP   SURFACE
(CIRCLE)

BOTTOM   SURFACE
(COMPLEX)
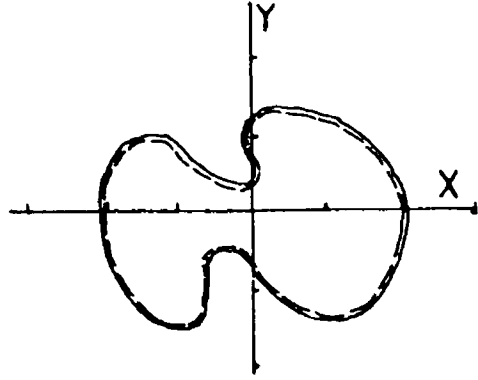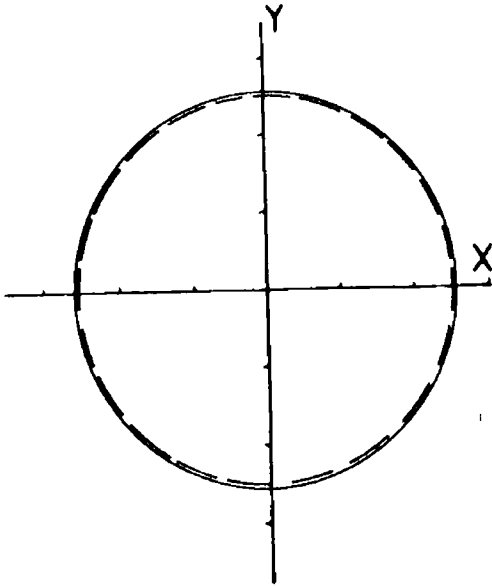
_____ = Generated profile   _ _ _ _ = Desired profile

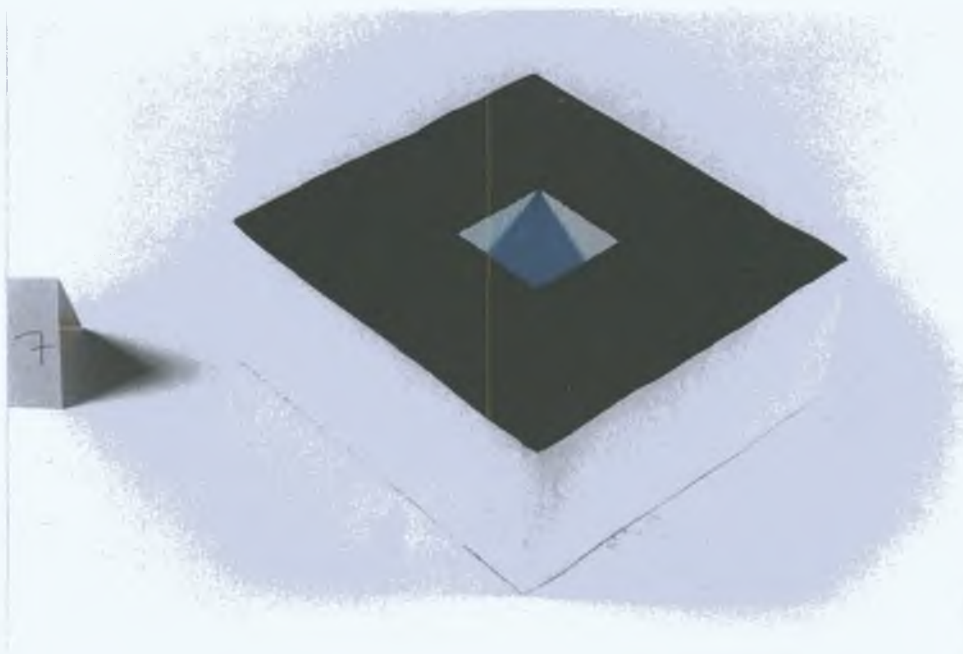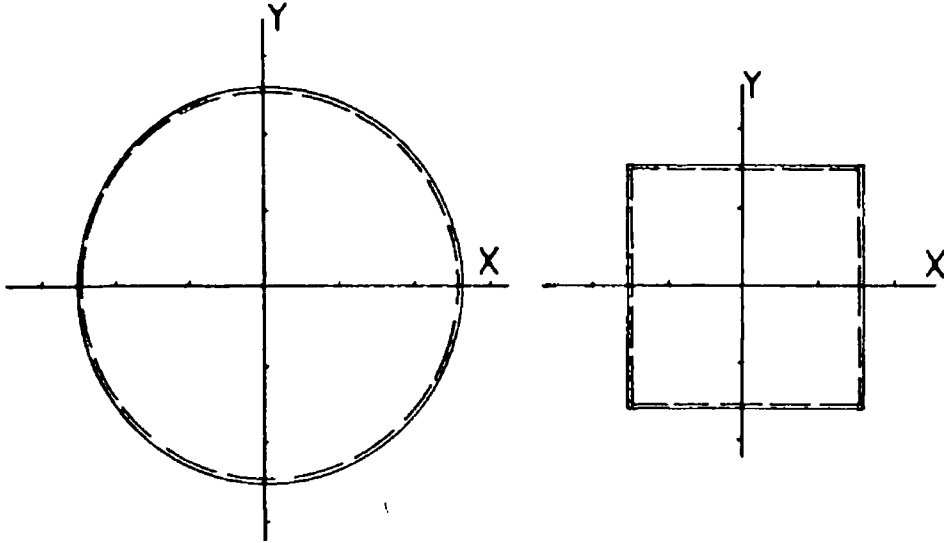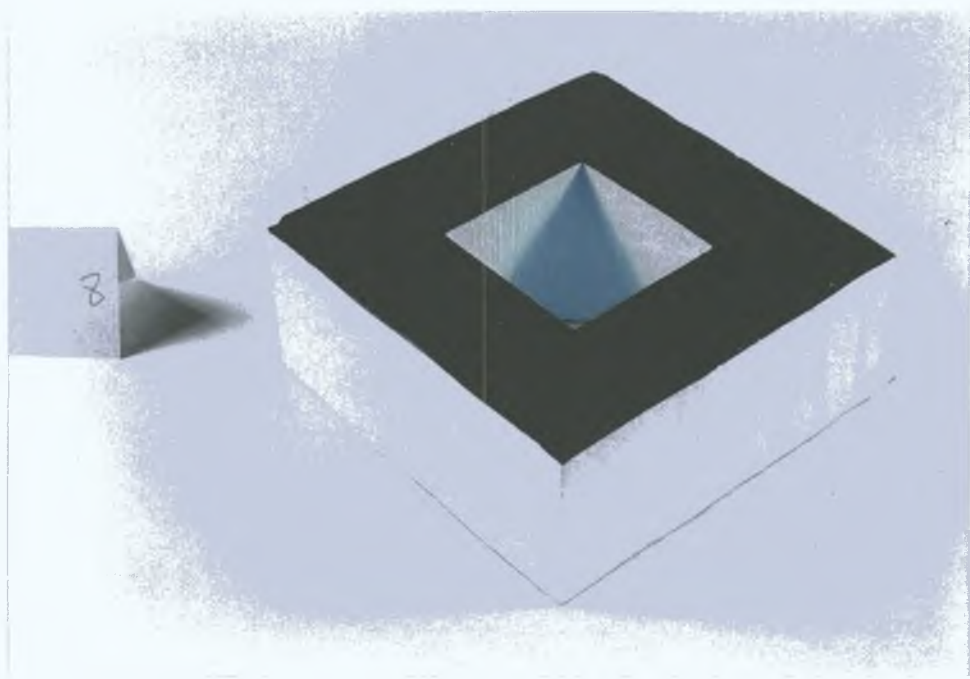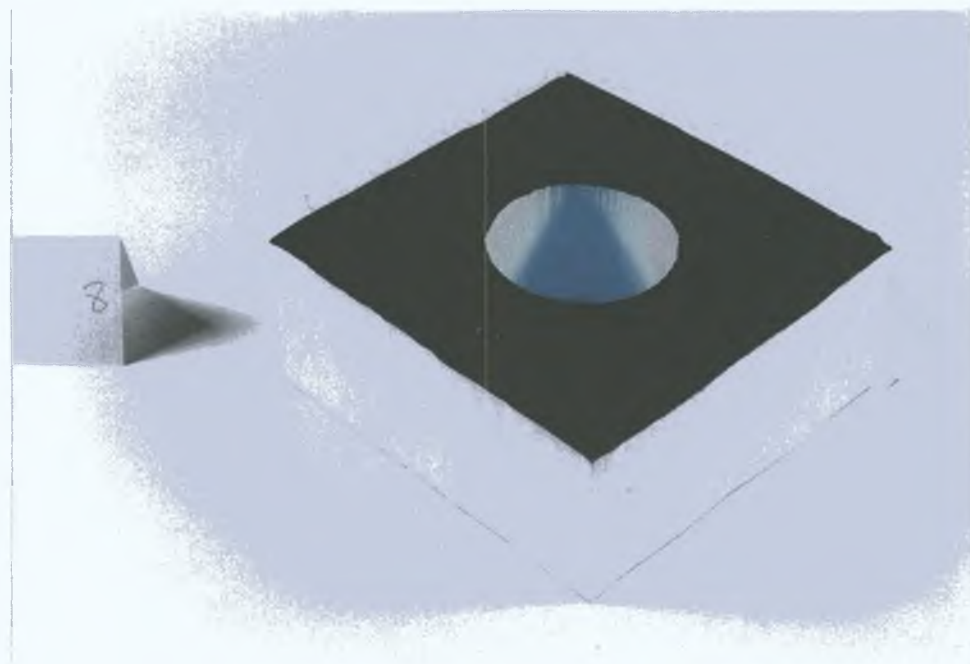(DATA FOR PLATE 7)

Number of points on the profile = 100
Top surface magnification (mm) = 25
Bottom surface magnification (mm)= 20
Workpiece thickness (2T) (mm)   = 49
Workpiece feedrate (mm^2/min) = 600
Voltage supplied to cutting wire = 5 5 Volts
Wire cutting path in millimeters = .5
Total machining area (mm^2)   = 19456.288
Total theoretical machining time = 15' 45.62''
Total practical machining time   = 28' 24.9''
Total time difference   = 12' 39.28''

FIGURE 72.   Theoretical and practical profile generation
for CIRCLE to COMPLEX shape
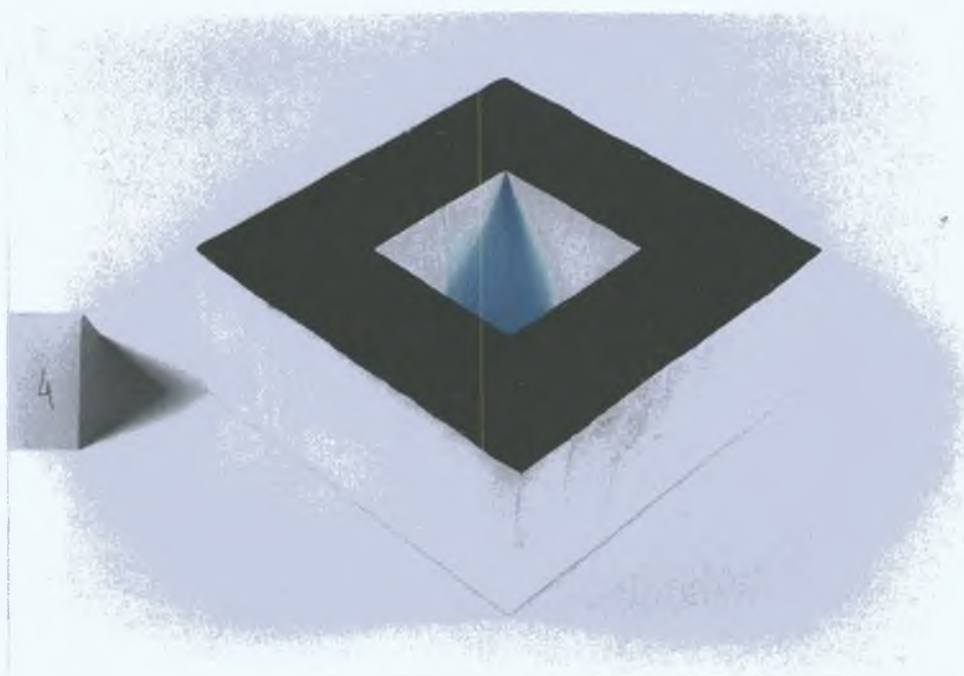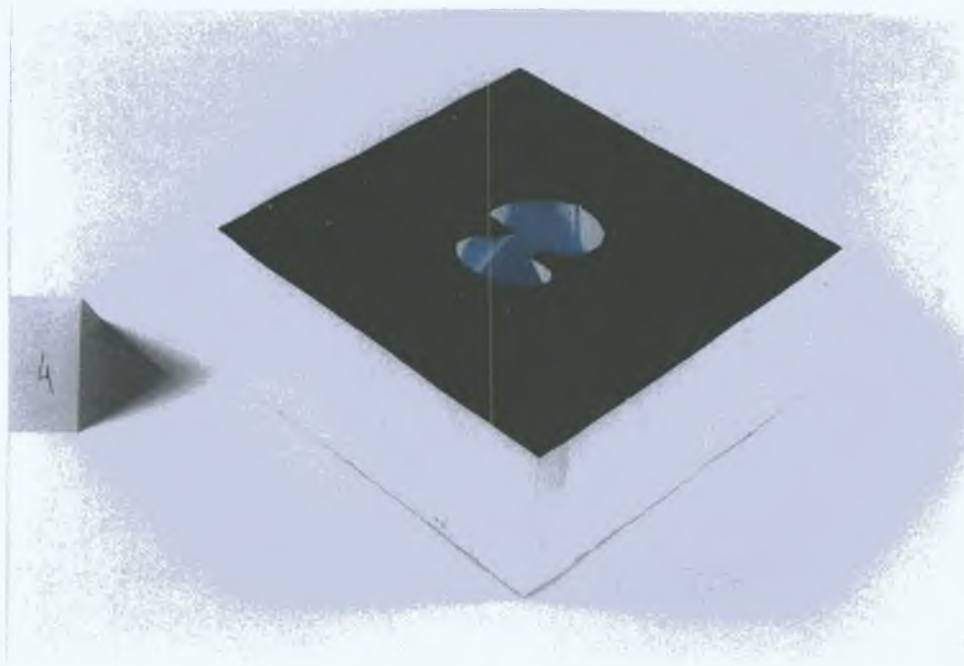
TOP SURFACE

BOTTOM SURFACE

PLATE 8.   SQUARE TO COMPLEX

TOP   SURFACE   BOTTOM   SURFACE
(SQUARE)   (COMPLEX)
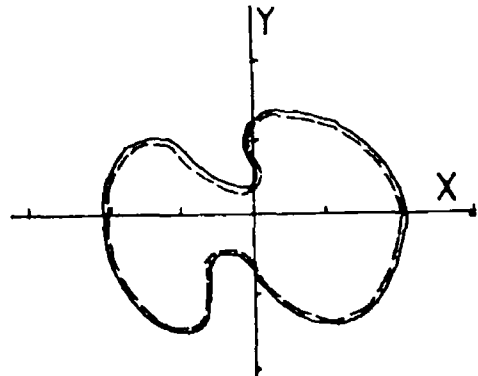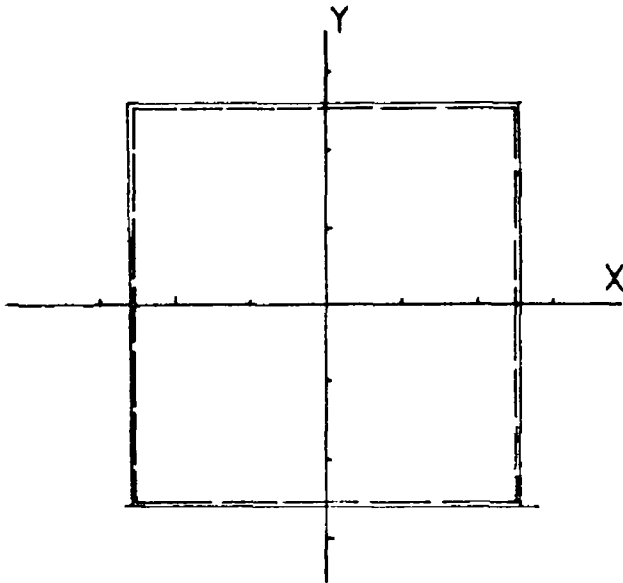
_____ = Generated profile   _ _ _ = Desired profile

<u>(DATA FOR PLATE 8)</u>

Number of points on the profile   = 80
Top surface magnification (mm)   = 25
Bottom surface magnification (mm)= 20
Workpiece thickness (ZT)   (mm)   = 49
Workpiece feedrate   (mm^2/min) = 500
Voltage supplied to cutting wire = 5 5 Volts
Wire cutting path in millimeters = .5
Total machining area   (mm^2)   = 10506.55
Total theoretical machining time = 21'   .785''
Total practical machining time   = 28'   75''
Total time difference   = 6' 59 965''

<u>FIGURE 73.   Theoretical and practical profile generation</u>
<u>for SQUARE to COMPLEX shape</u>
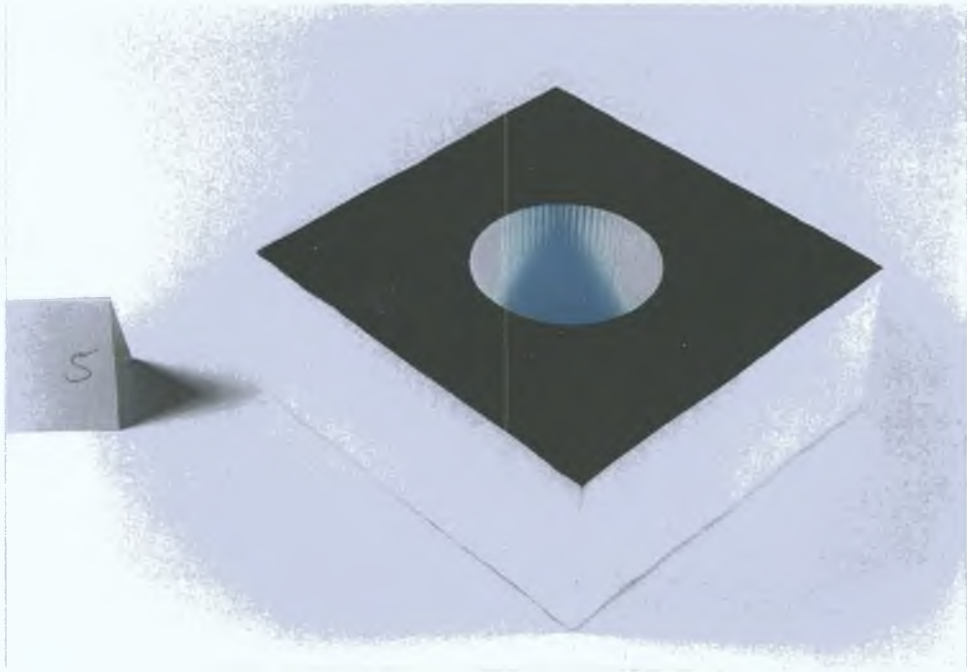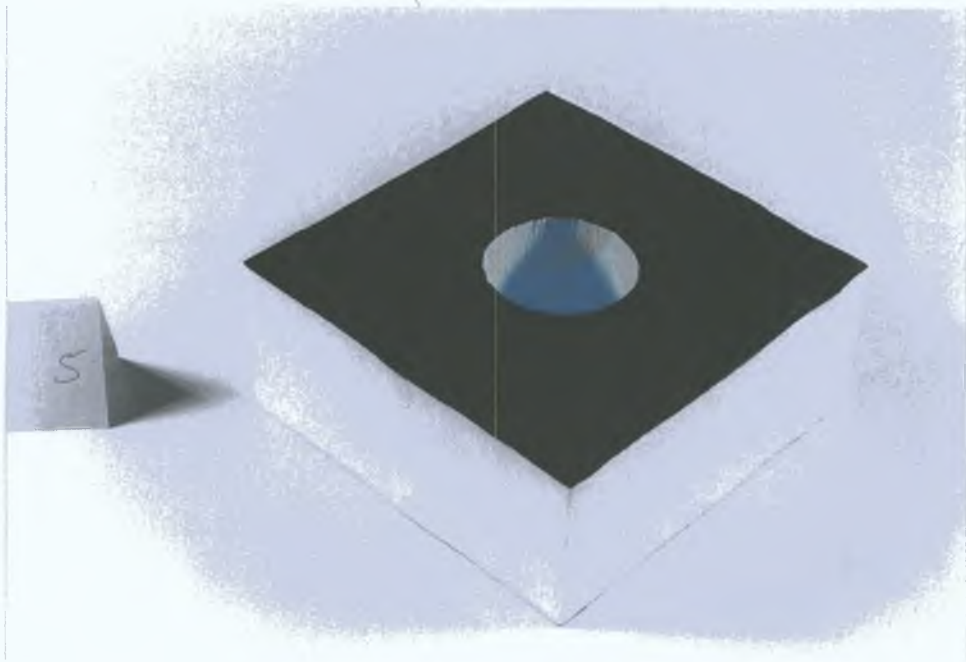
TOP SURFACE
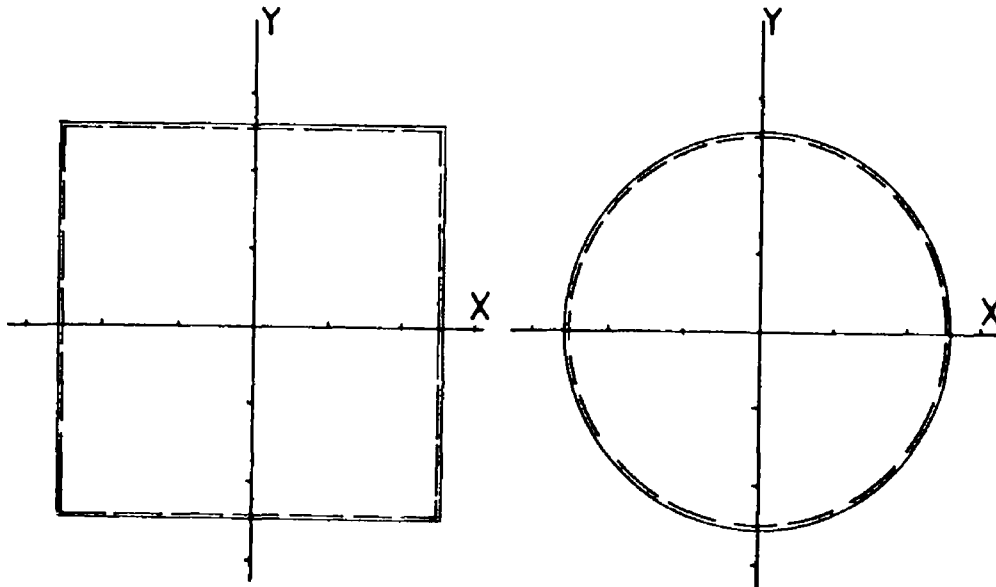

BOTTOM SURFACE

PLATE 9. CIRCLE TO CIRCLE
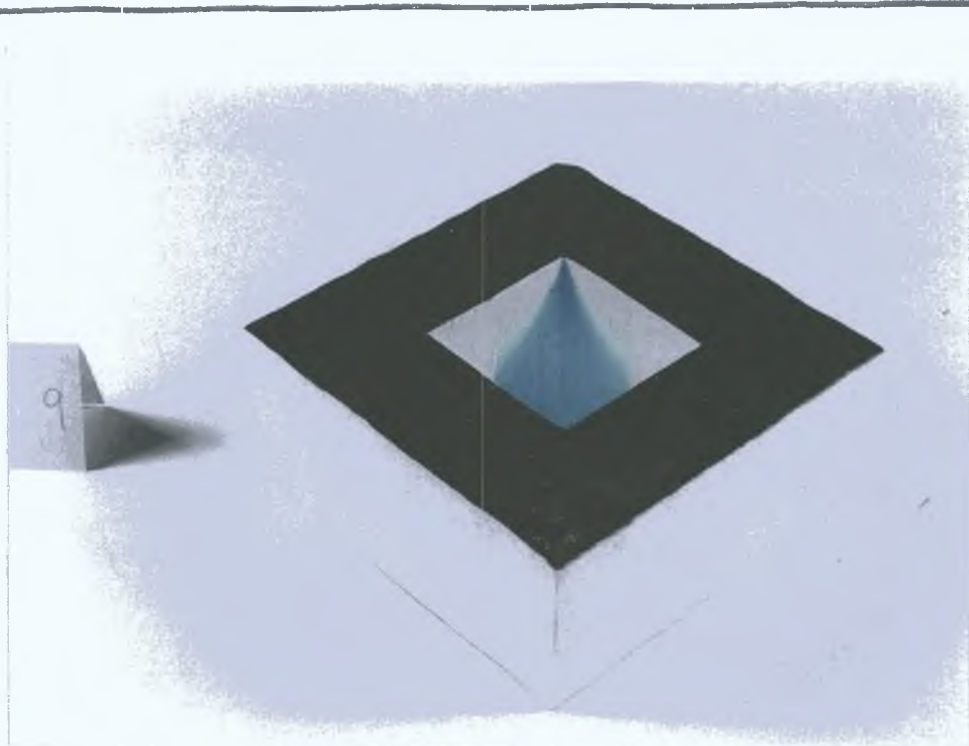
TOP SURFACE
(CIRCLE)

BOTTOM SURFACE
(CIRCLE)
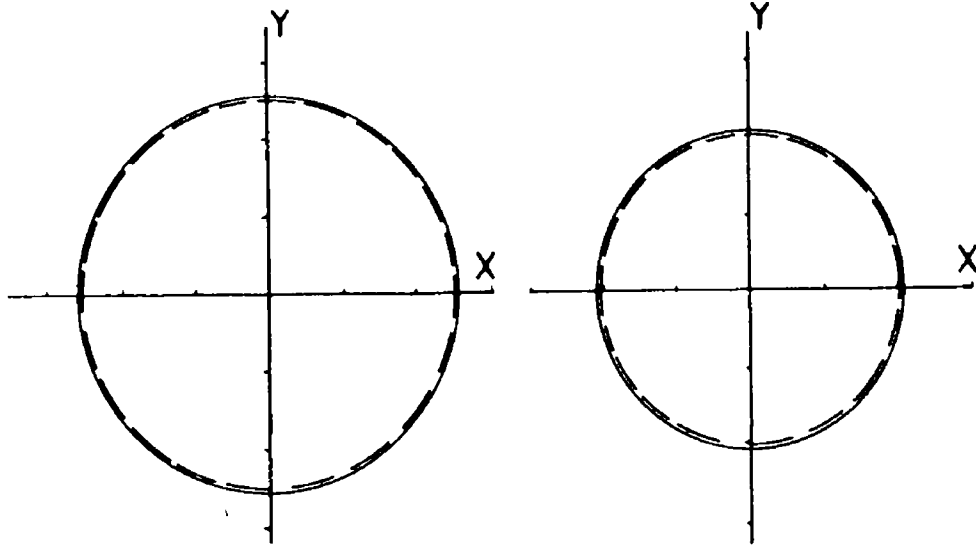
_____ = Generated profile   _ _ _ = Desired profile
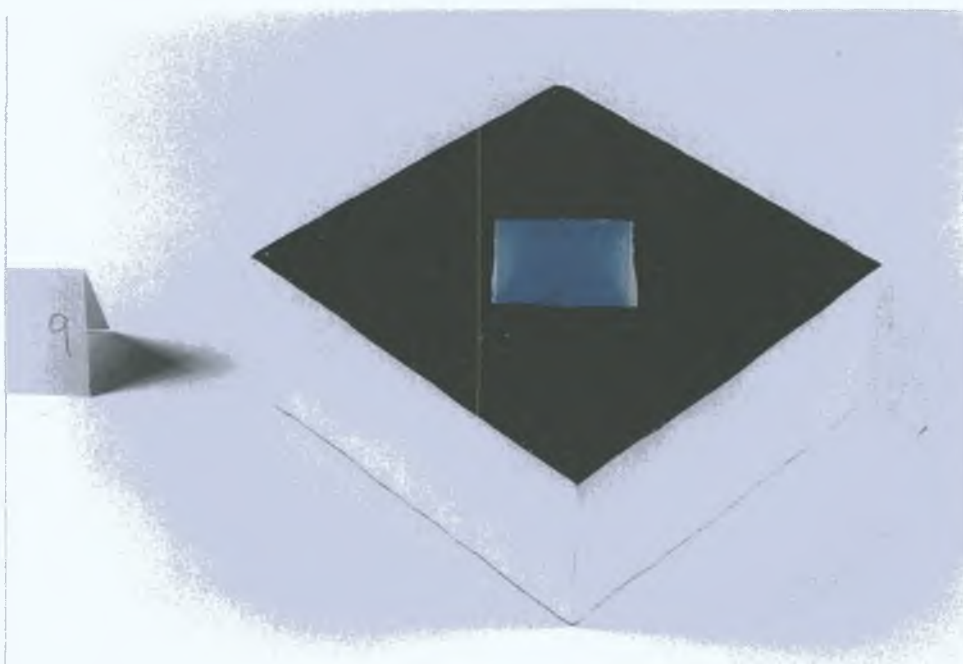
<u>(DATA FOR PLATE 9)</u>

Number of points on the profile   = 80
Top surface magnification   (mm)   = 25
Bottom surface magnification (mm) = 20
Workpiece thickness (ZT)$_2$ (mm)   = 49
Workpiece feedrate   (mm^2/min)   = 800
Voltage supplied to cutting wire   = 5.5 Volts
Wire cutting path in millimeters   = .5
Total machining area   (mm^2)   = 9130.43
Total theoretical machining time = 11'   24.78''
Total practical machining time   = 19'   24.11''
Total time difference   = 7' 59 33''

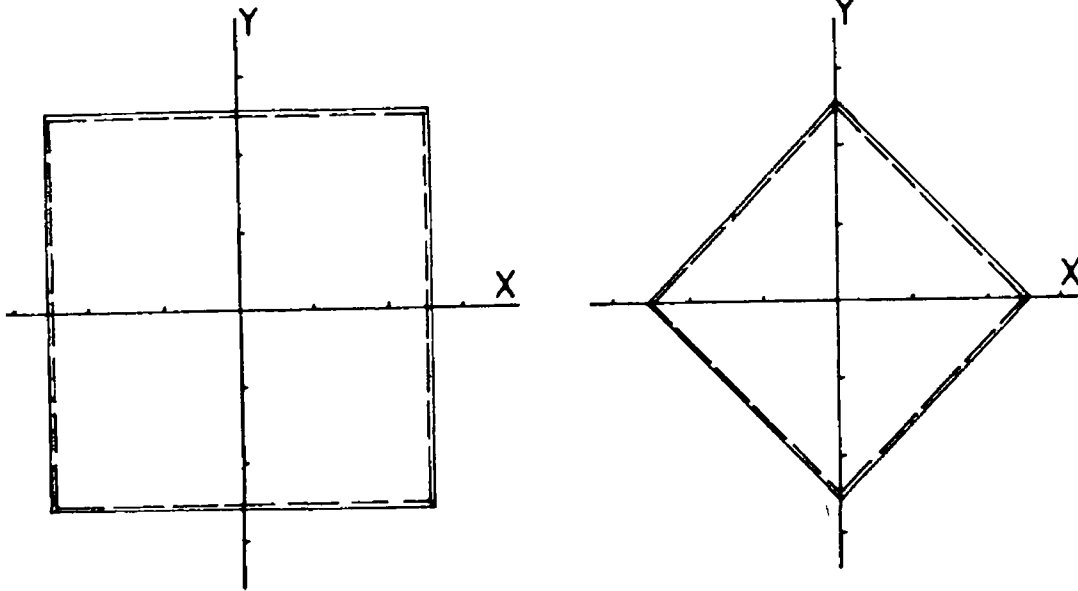**FIGURE 74.   Theoretical and practical profile generation
for CIRCLE to CIRCLE shape**

- 325 -
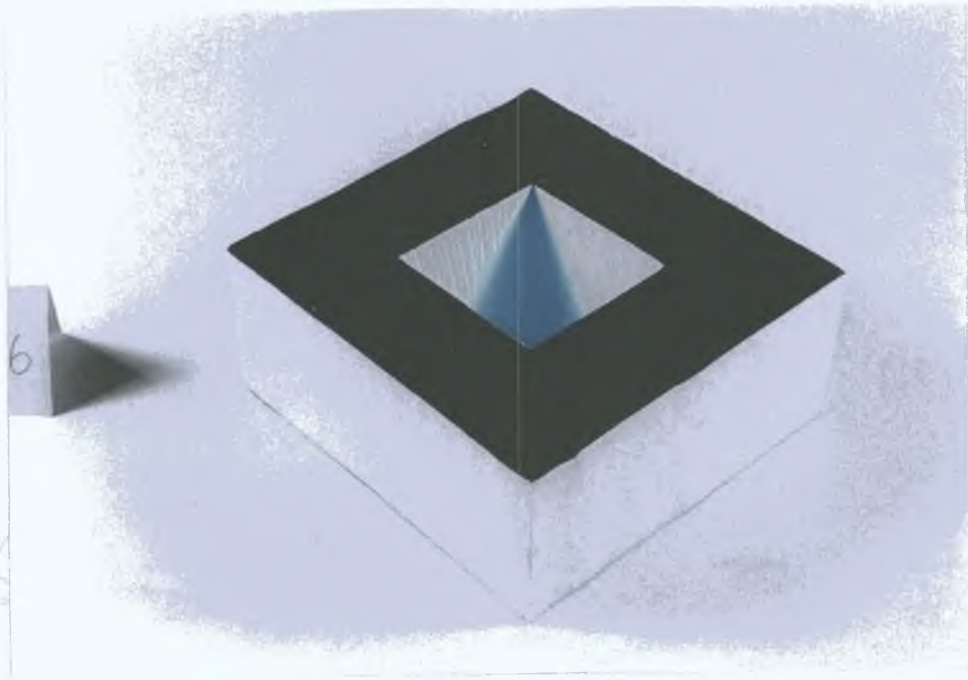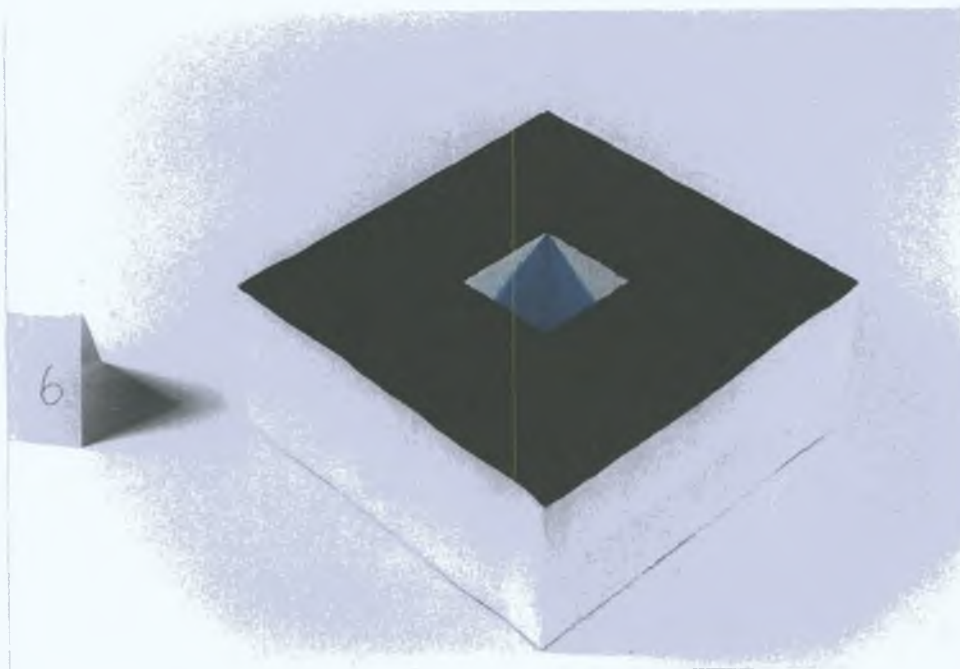
TOP SURFACE

BOTTOM SURFACE

PLATE 10.   SQUARE TO SQUARE

TOP   SURFACE
(SQUARE)

BOTTOM SURFACE
(SQUARE)
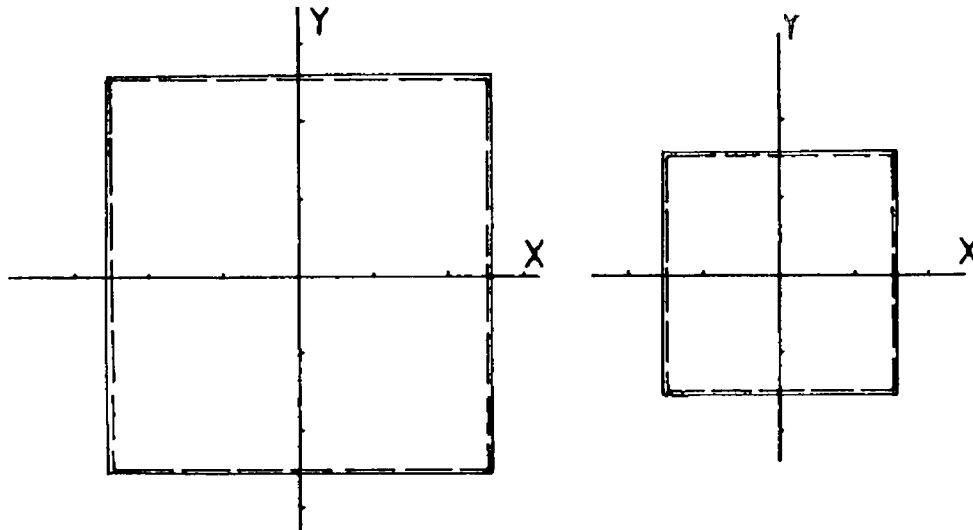
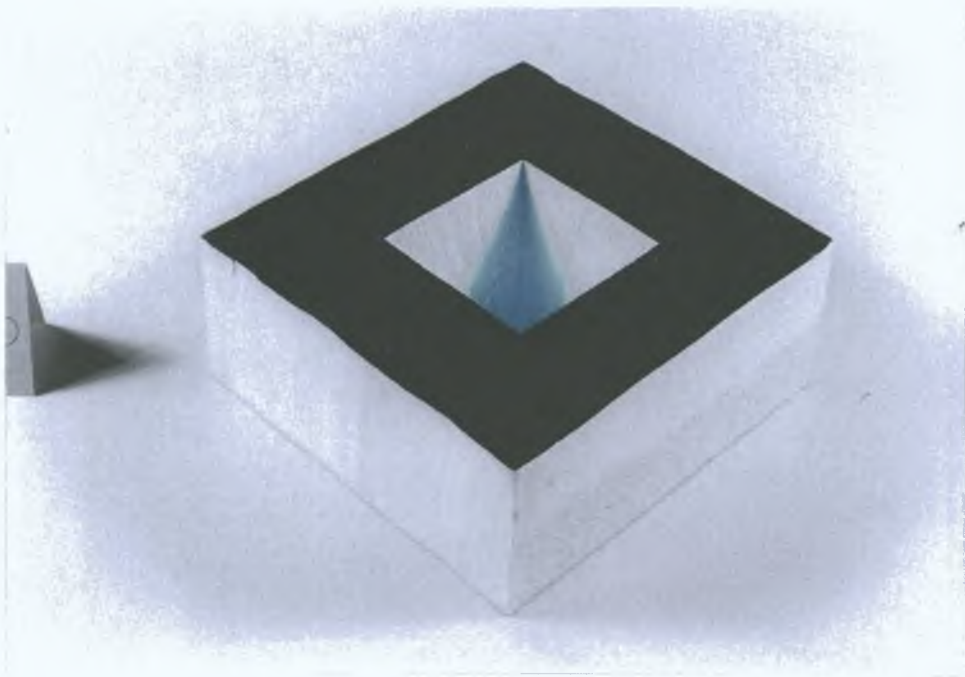_____ = Generated profile   _ _ _ = Desired profile

(DATA FOR PLATE 10)

```
Number of points on the profile   = 80
Top surface magnification    (mm) = 50 x 50
Bottom surface magnification (mm) = 30 x 30
Workpiece thickness (ZT)    (mm)  = 49
Workpiece feedrate    (mm²/min )  = 800
Voltage supplied to cuttin wire   = 5.5 Volts
Wire cutting path in millimeters  = .5
Total machining area     (mm²)    = 10611.86
Total theoretical machining time  = 13'  15 88''
Total practical machining time    = 19'   57.37''
Total time difference             = 6'  41.49''
```

FIGURE 75.   Theoretical and practical profile generation
for SQUARE to SQUARE shape

- 327 -

TOP SURFACE

BOTTOM SURFACE

PLATE 11. CIRCLE TO SQUARE

TOP   SURFACE
(CIRCLE)

BOTTOM SURFACE
(SQUARE)

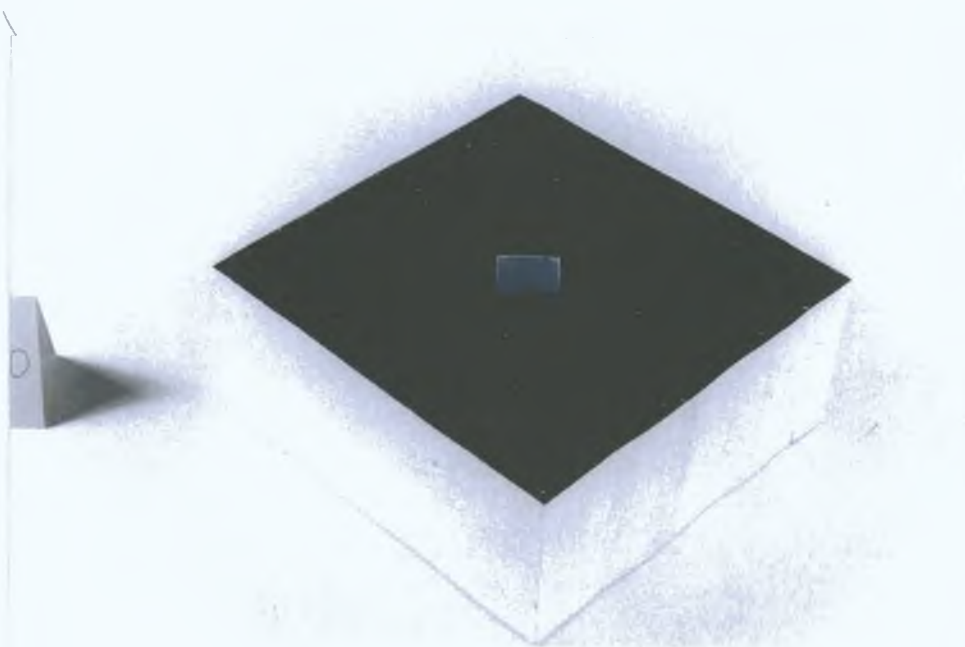_____ = Generated profile   _ _ _ = Desired profile

(DATA FOR PLATE 11)

Number of points on the profile   = 80
Top surface magnification (mm)   = 25
Bottom surface magnification (mm)   = 30 x 30
Workpiece thickness (ZT) (mm)   = 49
Workpiece feedrate   (mm^2/min) = 800
Voltage supplied to cutting wire   = 5.5 Volts
Wire cutting path in millimeters   = .5
Total machining area   (mm^2)   = 9051.91
Total theoretical machining time   = 11'   18.89''
Total practical machining time   = 20'   30 67''
Total time difference   = 9' 11.78''

**FIGURE 76.   Theoretical and practical profile generation
for CIRCLE to SQUARE shape**

TOP SURFACE

BOTTOM SURFACE

PLATE 12. SQUARE TO CIRCLE

TOP   SURFACE   BOTTOM SURFACE
   (SQUARE)   (CIRCLE)
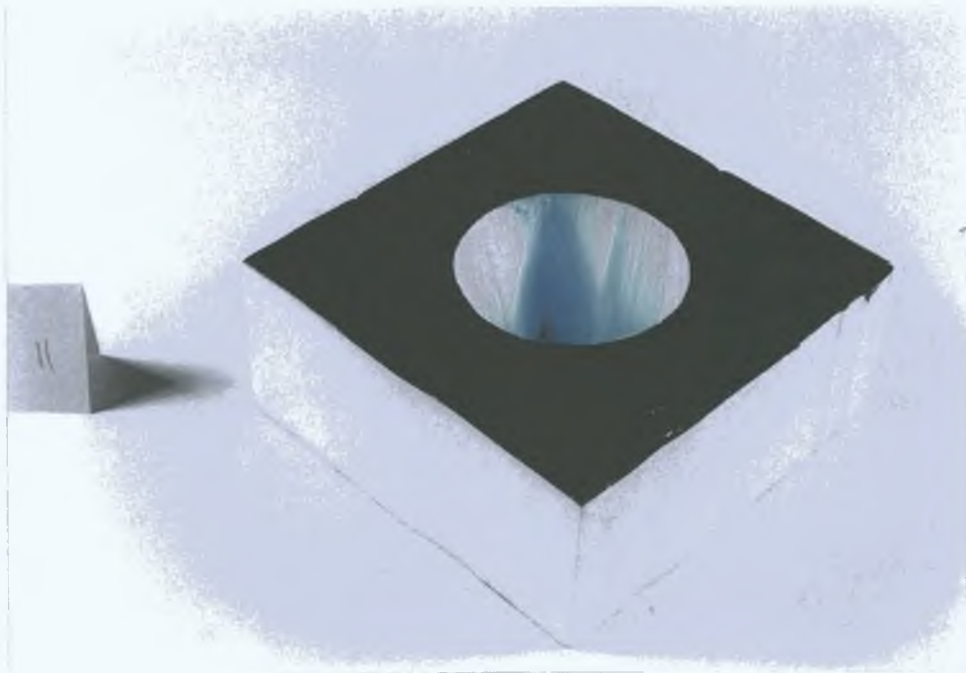

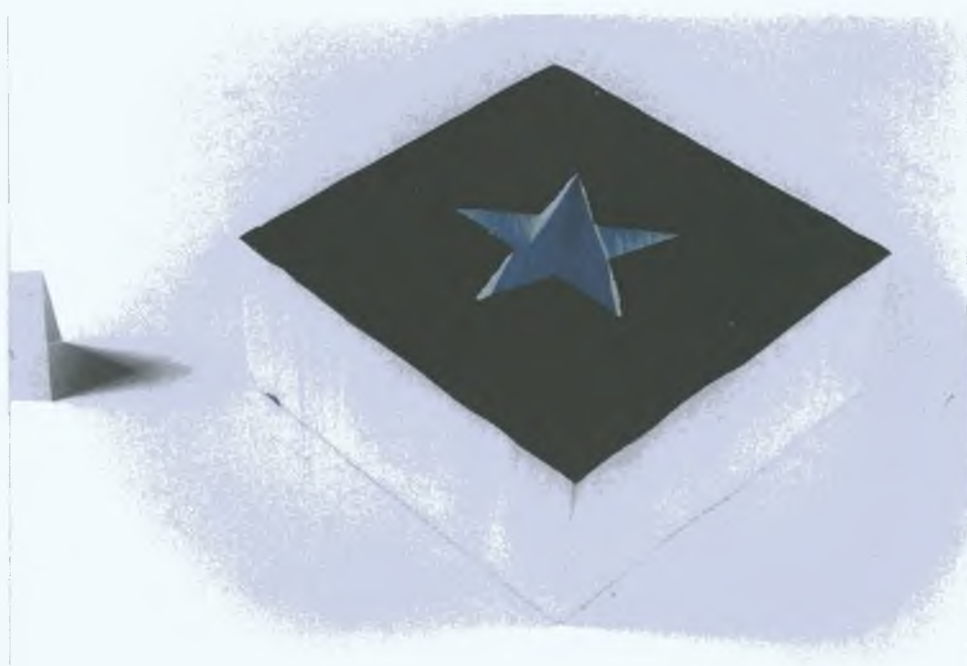_____ = Generated profile   _ _ _ = Desired profile

<u>(DATA FOR PLATE 12)</u>

Number of points on the profile = 80
Top surface magnification   (mm) = 50 x 50
Bottom surface magnification (mm)= 25
Workpiece thickness (2T)$_2$ (mm) = 49
Workpiece feedrate   (mm^2/min.) = 800
Voltage supplied to cuttin wire = 5 5 Volts
Wire cutting path in millimeters = 5
Total machining area   (mm^2)   = 11704 88
Total theoretical machining time = 14' 37 86''
Total practical machining time   = 22' 17.12''
Total time difference   = 7' 39 26''

<u>**FIGURE 77.   Theoretical and practical profile generation
             for SQUARE to CIRCLE shape**</u>

TOP SURFACE

BOTTOM SURFACE

PLATE 13. SQUARE TO SQUARE AT 90⁰ ROTATION

TOP   SURFACE   BOTTOM   SURFACE
(SQUARE)   (SQUARE AT 90°)

_____ = Generated profile   _ _ _ = Desired profile

(DATA FOR PLATE 13)

Number of points on the profile   = 80
Top surface magnification   (mm) = 25
Bottom surface magnification (mm) = 25
Workpiece thickness (ZT)$_2$ (mm)   = 49
Workpiece feedrate   (mm^2/min.)   = 600
Voltage supplied to cuttin wire   = 5.5 Volts
Wire cutting path in millimeters = 5
Total machining area   (mm^2)   = 10814 82
Total theoretical machining time = 18'   1.48''
Total practical machining time   = 22' 58.6''
Total time difference   = 4' 57.12''

**FIGURE 78.   Theoretical and practical profile generation
for SQUARE to SQUARE at 90° rotation.**
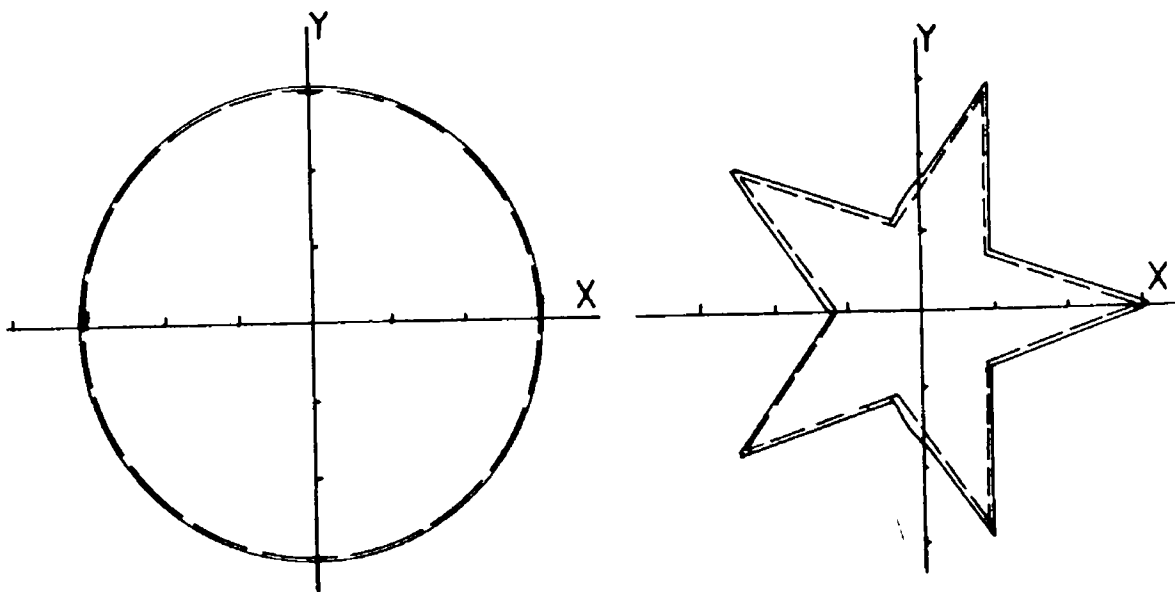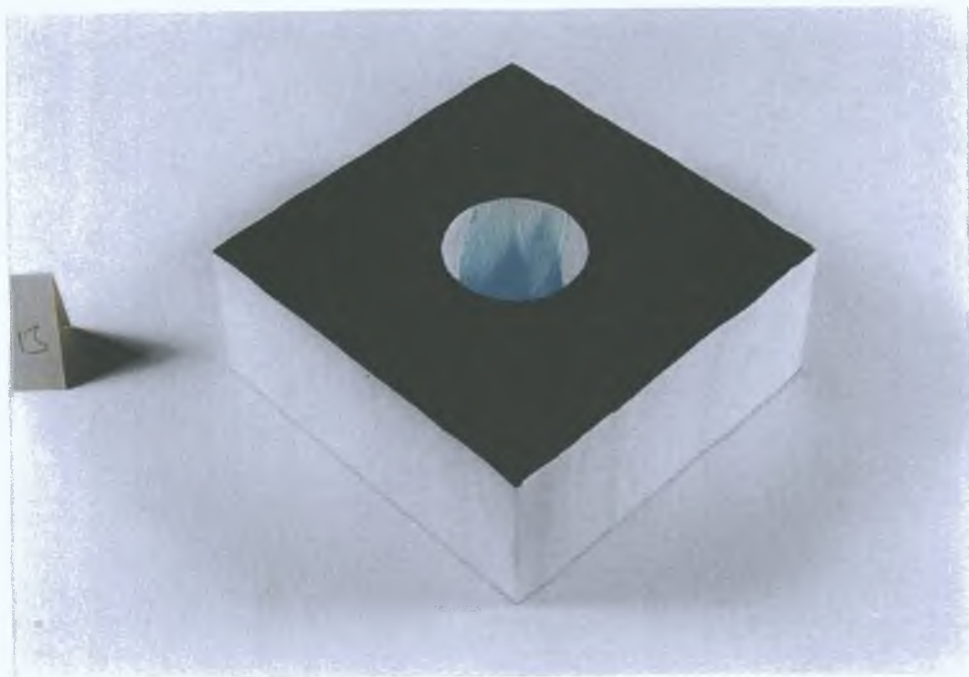
TOP SURFACE

BOTTOM SURFACE

PLATE 14.   SQUARE TO SMALLER SQUARE

AT 90^0 ROTATION

TOP SURFACE
(SQUARE)

BOTTOM   SURFACE
(SMALLER SQUARE
AT 90° ROTATION)
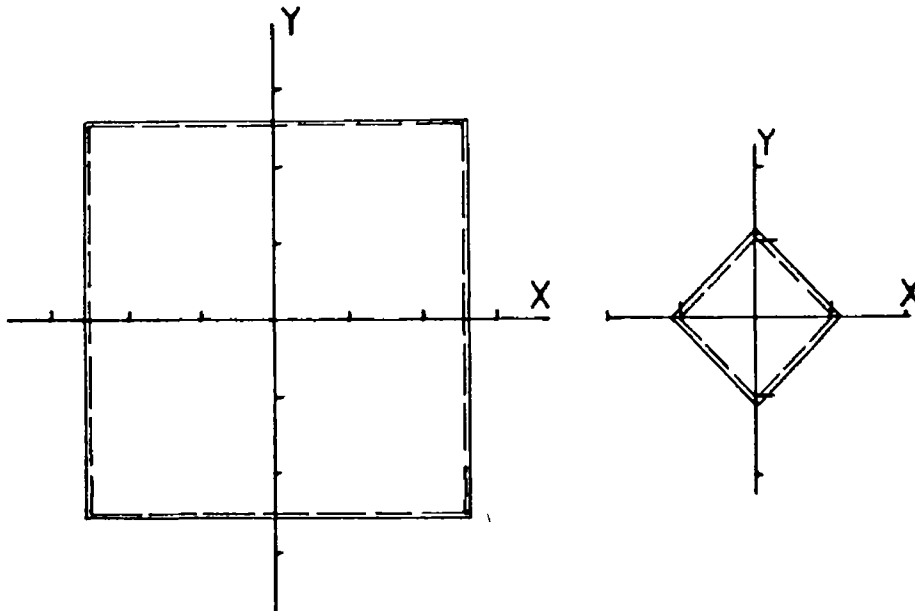
_____ = Generated profile   _ _ _ = Desired profile
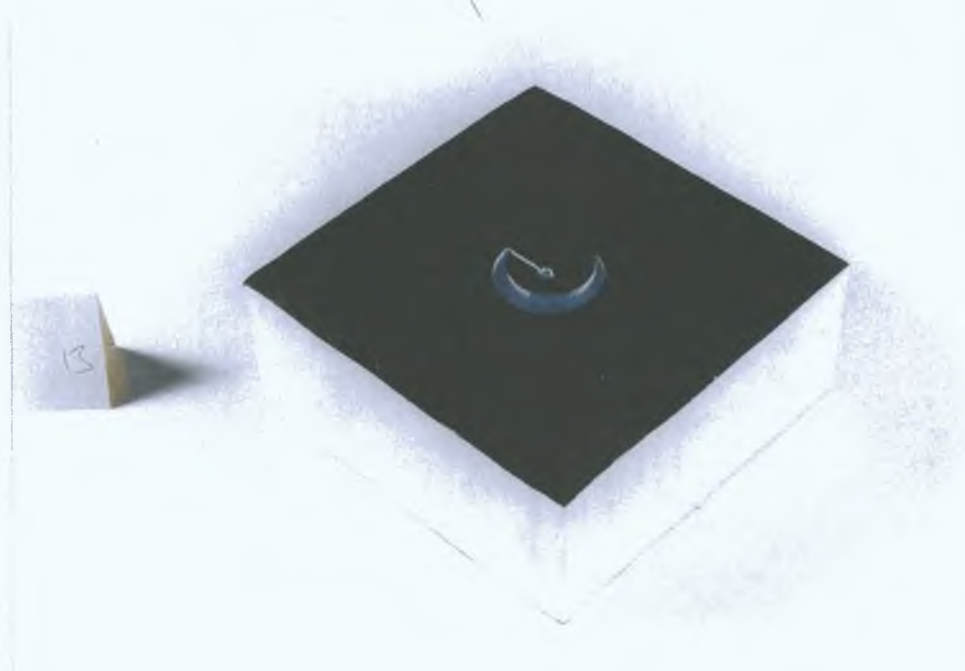
<u>(DATA FOR PLATE 14)</u>

Number of points on the profile   = 80
Top surface magnification   (mm) = 25
Bottom surface magnification (mm) = 10
Workpiece thickness (2T)   (mm) = 49
Workpiece feedrate   (mm^2/min) = 800
Voltage supplied to cutting wire = 5.5 Volts
Wire cutting path in millimeters = .5
Total machining area   (mm^2) = 8000.936
Total theoretical machining time = 10' 7.02''
Total practical machining time   = 15' 14.49''
Total time difference   = 5' 7.47''

**FIGURE 79,   Theoretical and practical profile generation
for SQUARE to SMALLER SQUARE at 90° rotation**

TOP SURFACE

BOTTOM SURFACE

PLATE 15.   CIRCLE TO STAR

TOP   SURFACE   BOTTOM SURFACE
      (CIRCLE)   (STAR)
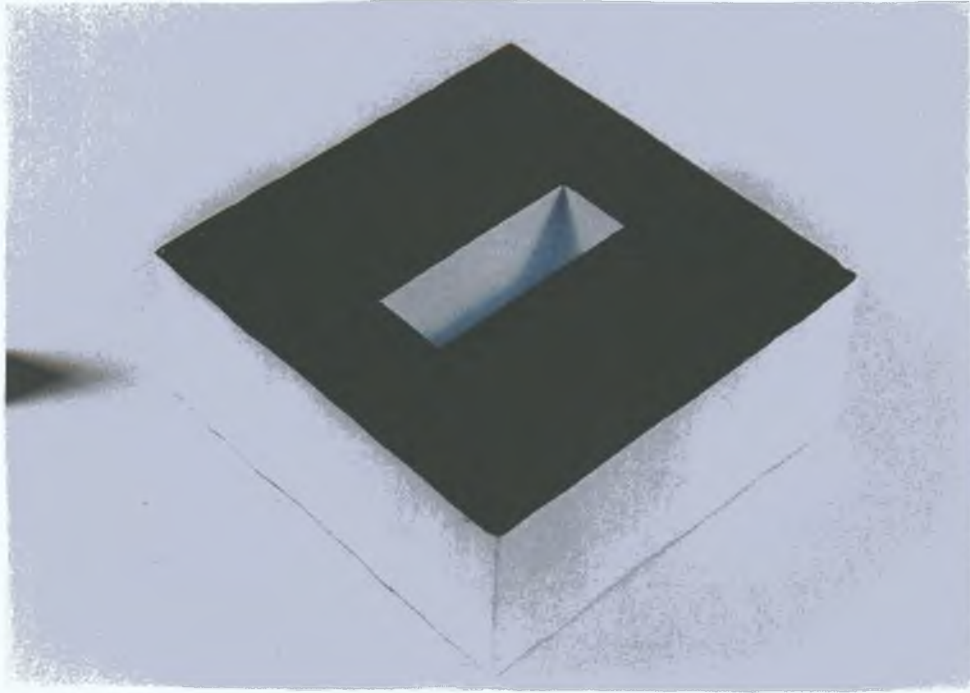

_____ = Generated profile   _ _ _ = Desired profile

(DATA FOR PLATE 15)

Number of points on the profile   = 80
Top surface magnification   (mm)= 30
Bottom surface magnification (mm)= 30
Workpiece thickness (ZT)   (mm) = 49
Workpiece feedrate   (mm^2/min) = 800
Voltage supplied to cuttin wire   = 5 5 Volts
Wire cutting path in millimeters = .5
Total machining area   (mm^2) = 12915.17
Total theoretical machining time = 16'   8.63''
Total practical machining time = 21'   15.9''
Total time difference   = 5' 7.27''

FIGURE 80.   Theoretical and practical profile generation
             for CIRCLE to STAR shape

TOP SURFACE

BOTTOM SURFACE

PLATE 16.   CIRCLE TO CRESCENT
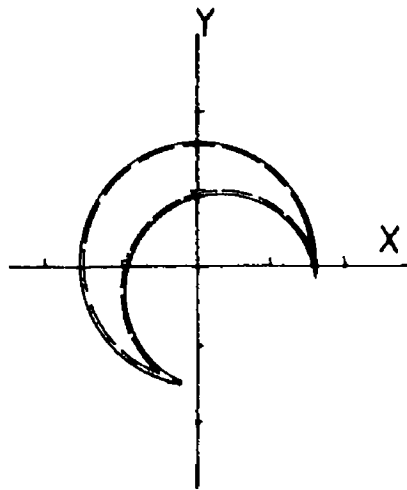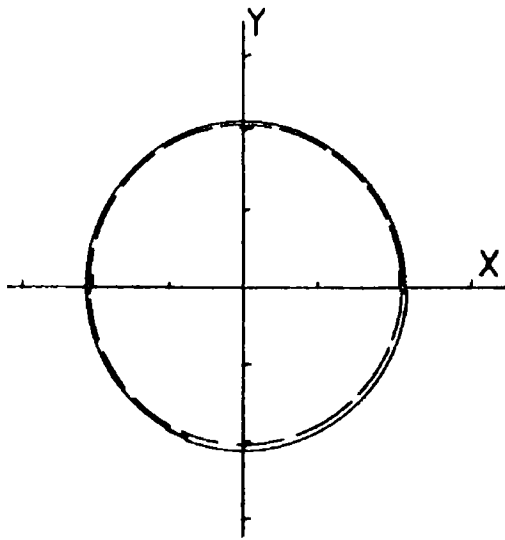
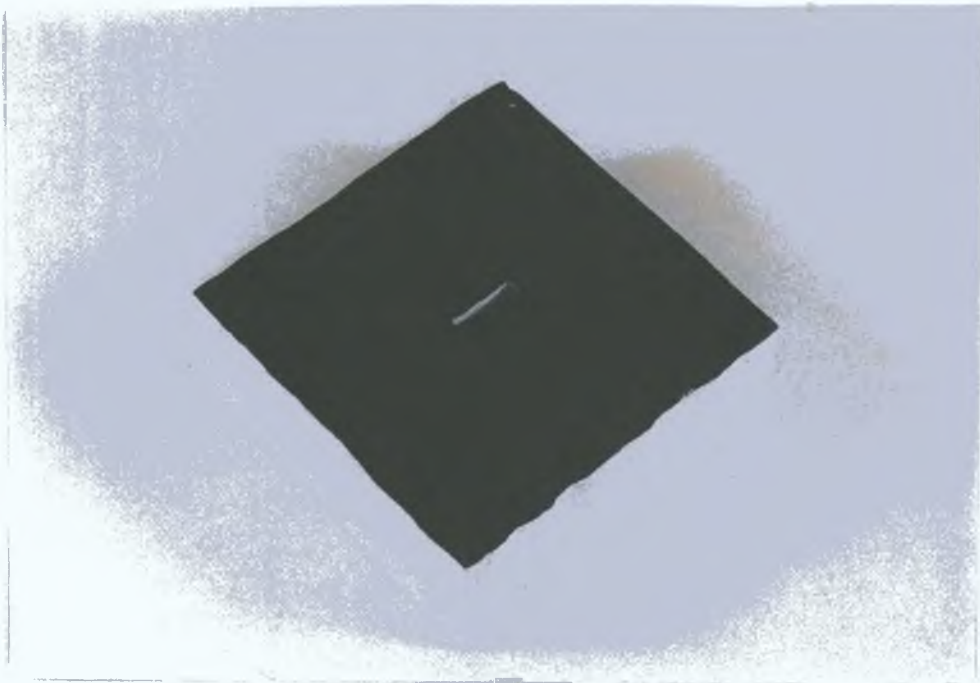_____ = Generated profile   _ _ _ = Desired profile

(DATA FOR PLATE 16)

```
Number of points on the profile  = 60
Top surface magnification (mm)    = 20
Bottom surface magnification (mm) = 15
Workpiece thickness (2T)   (mm)   = 49
Workpiece feedrate   (mm²/min )   = 800
Voltage supplied to cutting wire  = 5.5 Volts
Wire cutting path in millimeters  = .5
Total machining area     (mm²)    = 7609 85
Total theoretical machining time  = 9'    30.37''
Total practical machining time    = 15'   47.74''
Total time difference             = 6'  17.37''
```

**FIGURE 81.   Theoretical and practical profile generation
for CIRCLE to CRESCENT shape**

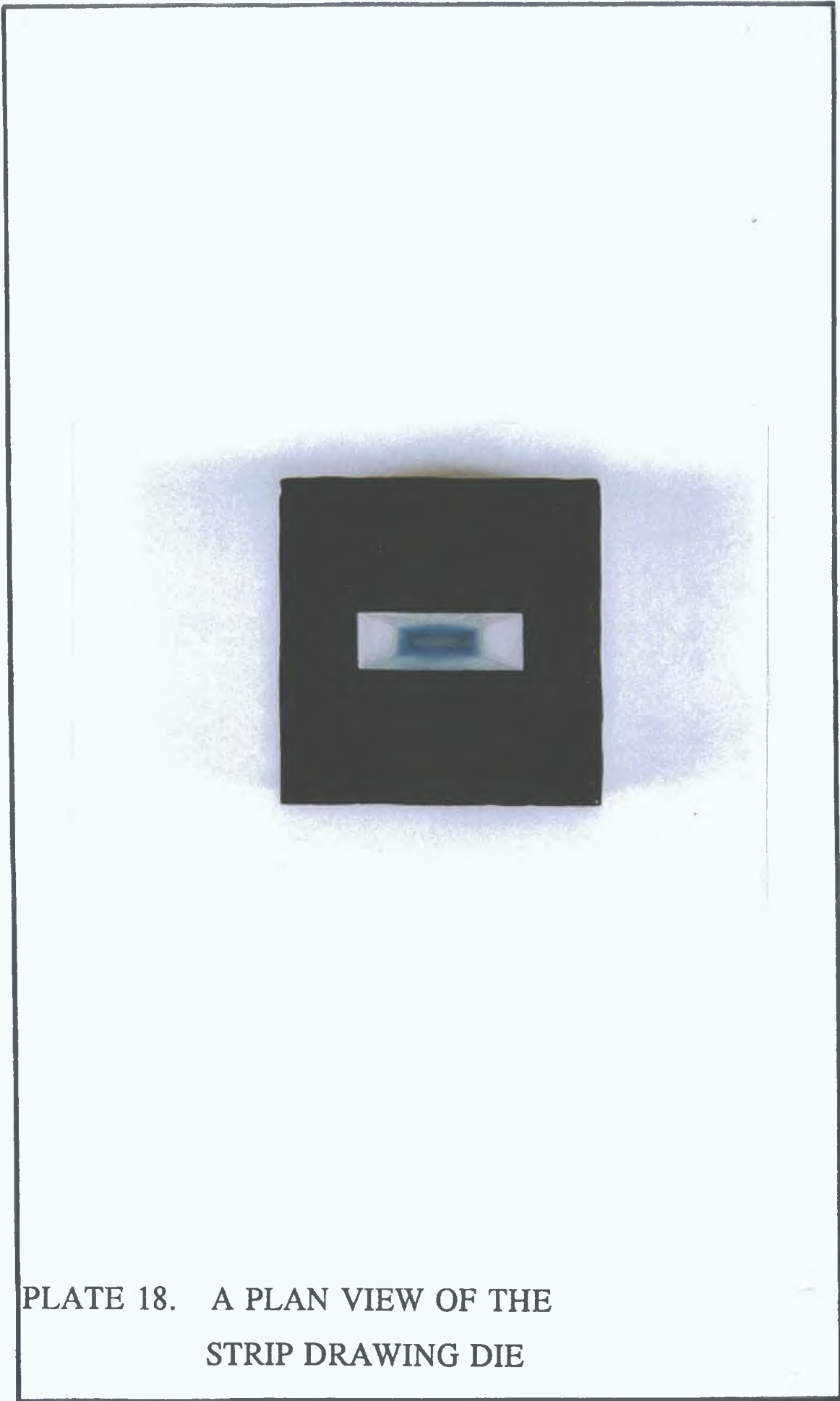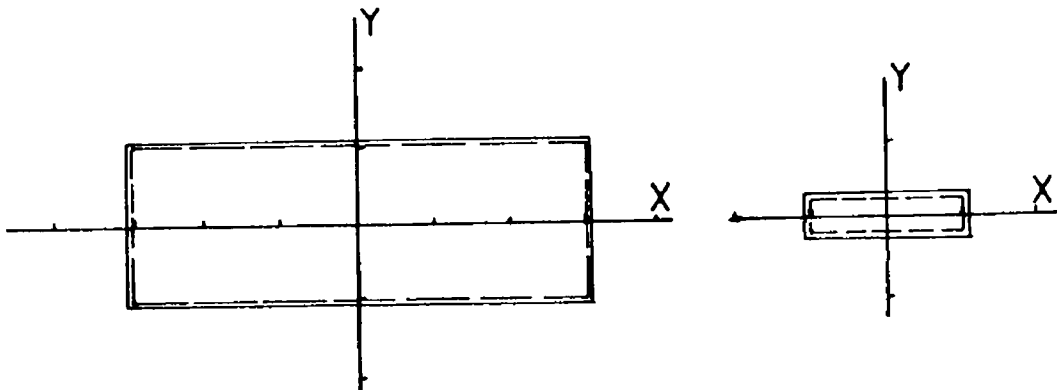TOP SURFACE

BOTTOM SURFACE

PLATE 17.   A STRIP DRAWING DIE

PLATE 18.   A PLAN VIEW OF THE
                 STRIP DRAWING DIE

TOP SURFACE   BOTTOM SURFACE
(BIGGER   (SMALLER
  RECTANGLE)   RECTANGLE)

_____ = Generated profile   _ _ _ = Desired profile
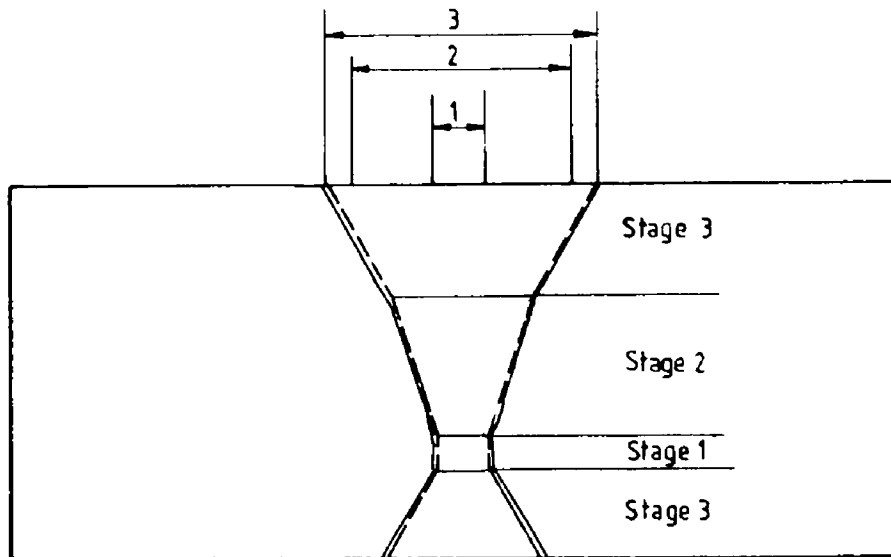
(DATA FOR PLATE 17 and 18)

Number of points on the profile   = 40
Top surface magnification (mm)   = 60 x 20
Bottom surface magnification (mm) = 20 x 4
Workpiece thickness (ZT)$_2$ (mm) = 49
Workpiece feedrate (mm^2/min) = 500
Voltage supplied to cutting wire   = 5.5 Volts
Wire cutting path in millimeters   = .5
Total machining area   (mm^2)   = 7145 72
Total theoritical machining time   = 14' 17.42''
Total practical machining time   = 17' 16.26''
Total time difference   = 2' 58.48''

**FIGURE 82.   Theoritical and practical profile generation
for STRIP DRAWING DIE**

PLATE 19.   A CIRCULAR TAPERED DIE

_____ = Generated profile   _ _ _ _ = Desired profile

<u>(DATA FOR PLATE 19)</u>

PARAMETERS		STAGE 1	STAGE 2	STAGE 3
Number of points on profile	= 60		60	60
Top surface magnification (mm)	=3.5		15	18
Bottom surface magnification	= 3.5		2	10
Workpiece thickness (mm)	= 49		49	49
Workpiece feedrate (mm^2/min)	= 400		500	500
Voltage supplied to wire	= 5 5 Volts		5 5 Volts	5 5 Volts
Wire cutting path (mm)	= .5		.5	5
Total machining area (mm^2)	= 1420.075		3448.71	5680 16
Total theoretical machining time ---------->	= 3' 33.01''		6'53 84''	11'21.6''
Total practical machining time ---------->	= 13'18.87''		14'11 13''	15'44.44''
Total time difference	= 9' 45.86''		7' 17.29''	4' 22.84''

<u>FIGURE 83.   Theoretical and practical profile generation</u>
<u>for a CIRCULAR TAPERED DIE</u>

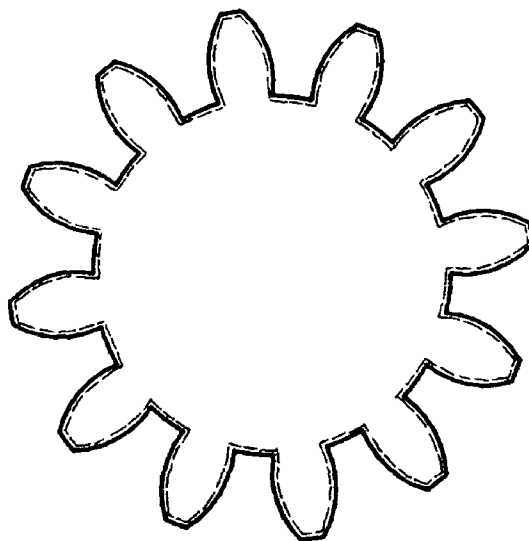- 344 -

PINION   GEAR WHEEL

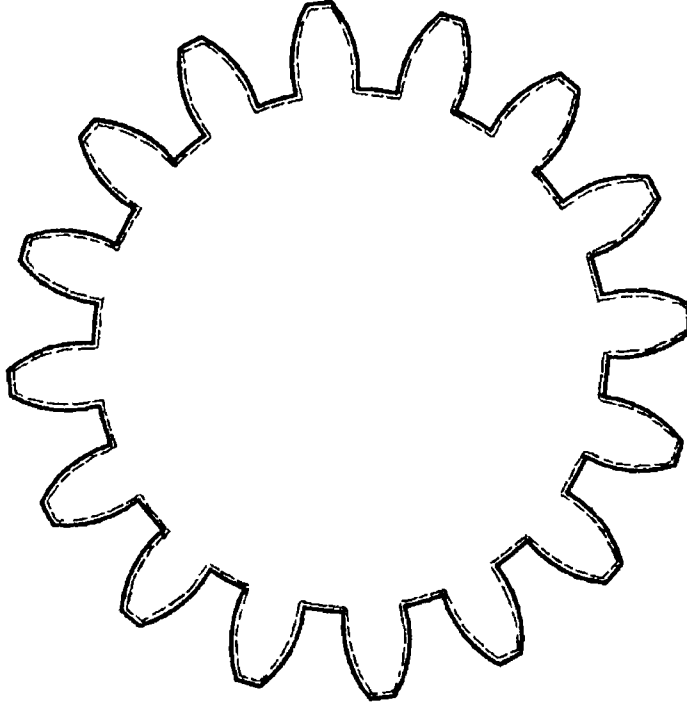PLATE 20.   A PINION AND A GEAR WHEEL IN MESH

PINION

_ _ _ _ = Generated profile   _____ = Desired profile

(DATA FOR PLATE 20 FOR A PINION)

Module	= 5
Pitch Circle Diameter (mm)	= 60
Pressure Angle (Degrees)	= 20
Number of teeth	= 12
Number of points on tooth curve	= 6
Total number of points on profile	= 250
Workpiece thickness (mm)	= 30
Workpiece feedrate (mm^2/min)	= 500
Voltage supplied to cutting wire	= 5 5 Volts
Wire cutting path approximately (mm)	= .5
Total machining area (mm^2)	= 13906.8
Total theoretical machining time	= 27' 48 8''
Total practical machining time	= 40' 53''
Total time difference	= 13' 4 2''

**FIGURE 84.   Theoretical and practical profile generation
for a PINION**

A GEAR WHEEL

_ _ _ = Generated profile   _____ = Desired profile

(DATA FOR PLATE 20 FOR A GEAR WHEEL

Module	= 5
Pitch Circle Diameter (mm)	= 80
Pressure Angle (Degrees)	= 20
Number of teeth	= 16
Number of points on tooth curve	= 6
Total number of points on profile	= 302
Workpiece thickness (mm)	= 30
Workpiece feedrate (mm^2/min)	= 600
Voltage supplied to cutting wire	= 5.5 Volts
Wire cutting path approximately (mm)	= 5
Total machining area (mm^2)	= 17208 24
Total theoretical machining time	= 28' 40 82''
Total practical machining time	= 45' 12 7''
Total time difference	= 16' 31.88''

**FIGURE 85.   Theoretical and practical profile generation
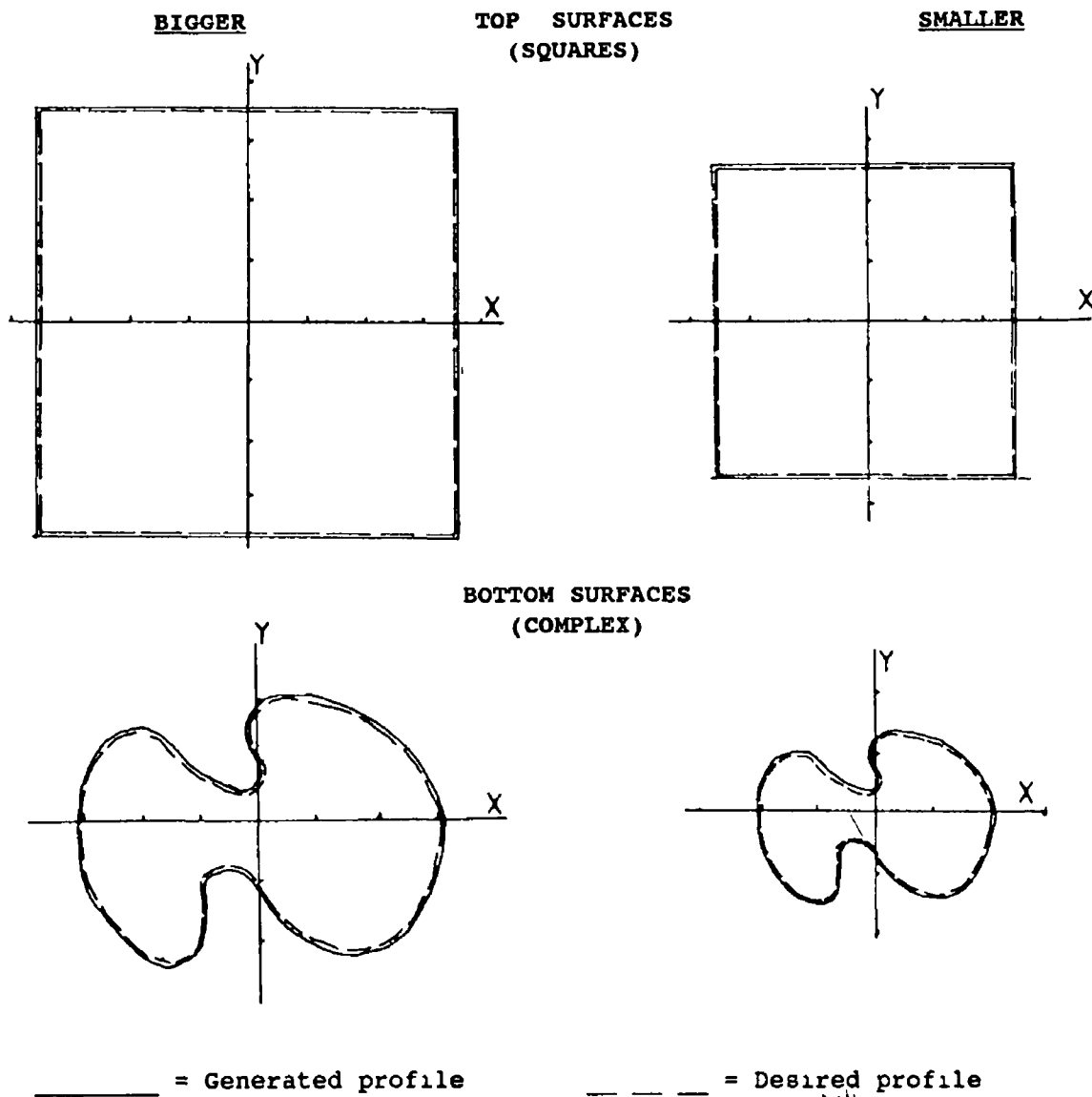for a GEAR WHEEL**
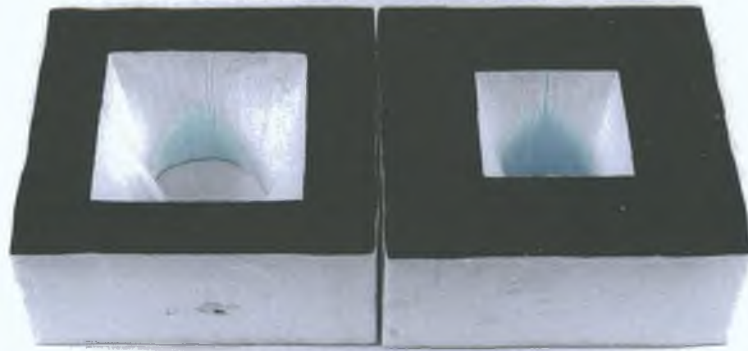
TOP SURFACE

BOTTOM SURFACE

PLATE 21. SQUARE TO COMPLEX OF

DIFFERENT SIZES
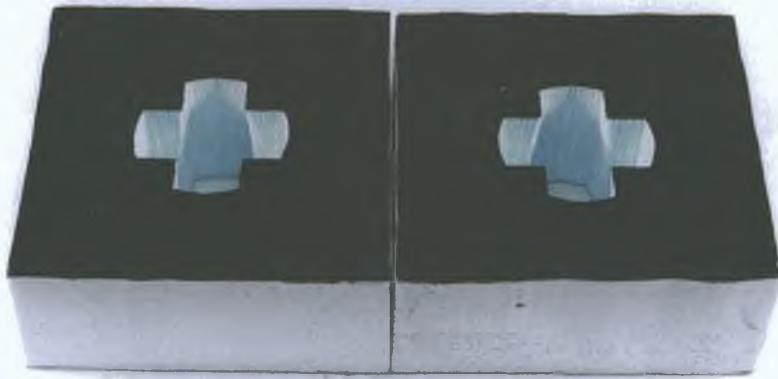
BOTTOM SURFACES
(COMPLEX)

_____ = Generated profile   _ _ _ = Desired profile

(DATA FOR PLATE 21)

PARAMETERS	BIGGER	SMALLER
Total number of points on profile=	80	80
Top surface magnification (mm) =	35 x 35	25 x 25
Bottom surface Magnification (mm)=	30	20
Workpiece thickness (mm) =	49	49
Workpiece feedrate (mm^2/min) =	800	500
Voltage supplied to cutting wire =	5 5 Volts	5 5 Volts
Wire cutting path (mm) =	5	.5
Total machining area (mm^2) =	15147 32	10506 55
Total theoretical machining time =	30' 17.67''	21' .785''
Total practical machining time =	35' 3.79''	28' .75''
Total time difference =	4' 46 12''	6' 59 965''

FIGURE 86   Theoretical and practical profile generation for
SQUARE to COMPLEX shapes of different sizes

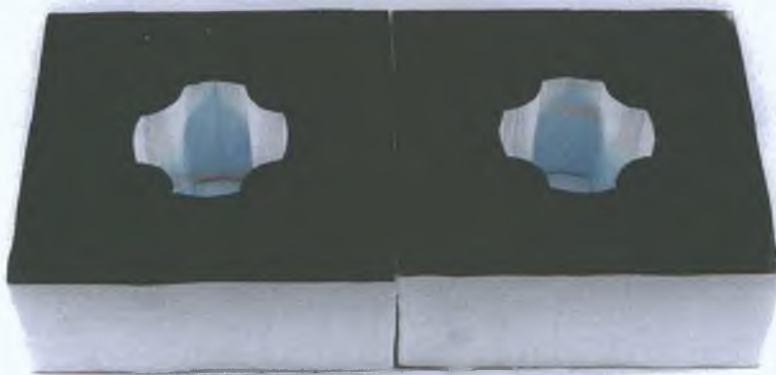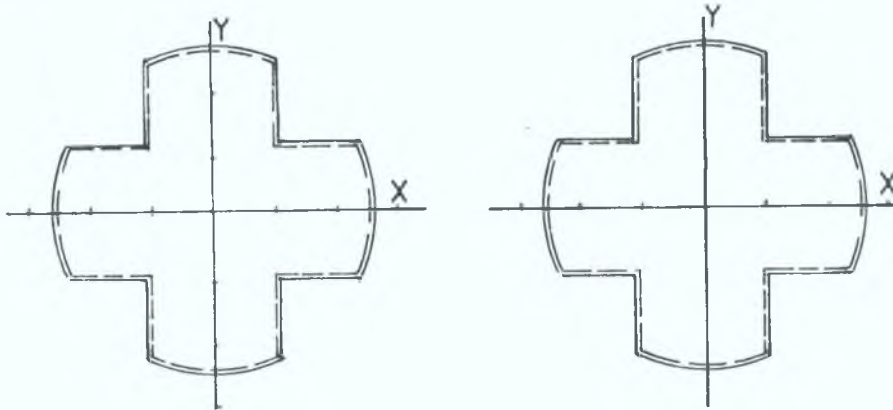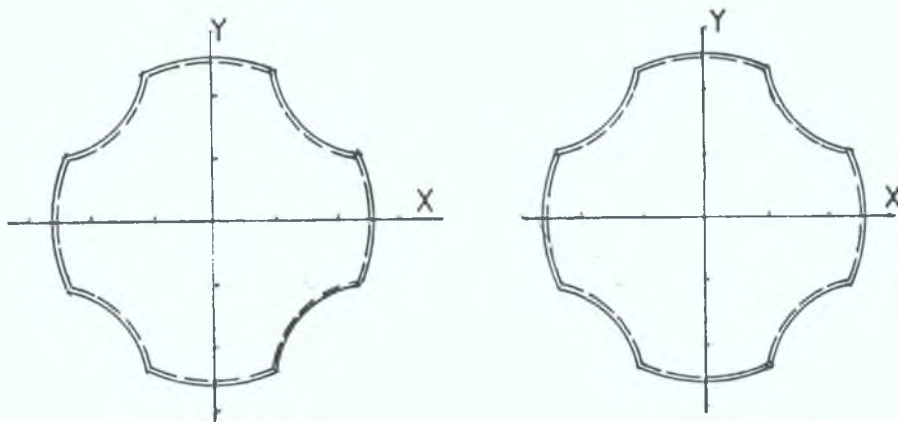ONE   TWO

TOP SURFACE

ONE   TWO

BOTTOM SURFACE

PLATE 22. STRAIGHT SIDE CROSS TO CURVED

SIDE CROSS AT DIFFERENT SPEEDS

TOP   SURFACES
(STRAIGHT SIDE CROSS)

ONE   TWO

BOTTOM SURFACES
(CURVED SIDE CROSS)

_____ = Generated profile   _ _ _ = Desired profile

(DATA FOR PLATE 22)

PARAMETERS	ONE	TWO
Total number of points on profile= 80		80
Top surface magnification (mm)= 50		50
Bottom surface magnification (mm)= 50		50
Workpiece thickness (mm) = 49		49
Workpiece feedrate (mm^2/min.) = 800		500
Voltage supplied to cutting wire = 5.5 Volts		5.5 Volts
Wire cutting path (mm) = .5		.5
Total machining area (mm^2) = 10930.96		10930.96
Total theoretical machining time = 13' 39.8''		21' 51.71''
Total practical machining time = 23' 52.1''		29' 47.7''
Total time difference = 10' 12.3''		7' 55.99''

FIGURE 87. Theoretical and practical profile generation for
          STRAIGHT SIDE CROSS to CURVED SIDE CROSS   at
          different speeds

- 351 -

CHAPTER SIX

CONCLUSION AND SUGGESTIONS FOR FUTURE WORK

6.1. CONCLUSION

The present research involved the feasibility study and design of a precision manipulator for the micro-computer controlled manufacture of 2-D/3-D complex shapes using WEDM process. The present design of the 4-axes precision manipulator has given greater angular flexibility of machining the 3-D complex shapes.

The software developed for controlling the manipulator and generating these complex shapes produced very satisfactory results under simulated cutting conditions. All 2-D/3-D shapes generated were observed to be in accordance with the appropriate prescribed geometry. The on-line process optimisation, by receiving trigger input signals and sending programmable outputs to the PVR circuit was also noticed to be functioning very satisfactorily, which is a step forward to the adaptive control optimisation. In particular, the control aspect of the precision manipulator under user selected machining conditions was very challenging which might lead to the manufacture of this unit on commercial basis, the unit being independent of the WEDM machine but having more angular cutting facility and cheaper. It should also be

noticed that the 3-D complex shapes produced confirmed that the four axes were sufficient to achieve the necessary manipulation of the workpiece around the cutting wire of a WEDM machine.

The speed of the process was noticed to be affected by the slow execution of the programs by the micro-computer and the uncompiled version of the programming language used.

For carrying out the tests on a real WEDM machine the physical design of the manipulator will need to be modified to facilitate the sealing of the motors from splashes of the dielectric fluid. More sensing circuits are also required to be connected with the trigger input and programmable output connectors of the PC23 indexers for different on-line conditions to be optimized in the WEDM process.

6.2. SUGGESTIONS FOR FUTURE WORK

As it is mentioned in earlier sections that the present design of the precision manipulator is not suitable for the real WEDM process since the workpiece should be immersed in the dielectric fluid or co-axial jets of the dielectric fluid should be arranged to produce a suitable environment for the spark in the gap between the workpiece and the cutting wire A number of on-line machining parameters also need to be monitored, so that the optimum

system performance can be achieved. Therefore, the hardware and software for the whole system needs to be modified.

The workpiece housing parts (inner and outer C frames) should be made from a rust proof material, and all of its bearings need to be protected from the minute particles of the eroded metallic material in the dielectric fluid. The lead screws for the linear motion should also be changed with ball screws to achieve smoother and backlash free motion, which will also reduce the frictional forces. The gear box for the rotary motion beta (motor 3) also needs to be changed to a smaller size and reduced backlash and higher gear ratio, so that improved manipulation along the Y-axis can be produced.

In the present design of the manipulator, three of the four motors are positioned away from the vicinity of the working zone. This design allows to isolate these three motors from the splashes of the dielectric fluid during machining process by means of a plastic sheet or other suitable material. The fourth motor for the angular motion alpha is located in the vicinity of the cutting zone and needs to be sealed for protection from dielectric fluid. Under such condition a jet system can be used for flushing the debris, rather than immersing the entire working area in dielectric fluid.

For more reliable operation and precisely accurate manufacture of the components, the manipulator needs to

have the means of verifying the positional accuracy, which is not guaranteed at present. In the present system the only feedback being verified is for the pulses sent to the motor and for the current motor shaft position between the resolver attached to the motor shaft and the KS-drive. If there is any inaccuracy this will be corrected. There is no feed back to the PC23 indexer from the load related position. The installation of the encoder is very important for compensating the backlash of the lead screw, gear boxes or other loose parts of the manipulator assembly, which might occur during the operation. The motor resolution can also be further increased upto 10000 steps/revolution on the PC23 indexer and 16384 steps/revolution on the KS-drive for improved precision.

Installing the CW and CCW limit switches are also very important for the safety of the manipulator and reliable execution of the WEDM process. Any mistake by the programmer can lead to the damage to the manipulator. There is no assurance against these kinds of mistakes.

By installing the "home position" switch, the initial set up time for any shape to be manufactured will be greatly reduced. The software named 'CONTROL.BAS' given in appendix C9 (volume II) can easily be modified, so that the user needs only to input the X and Y co-ordinates for the cutting wire to be positioned.

For different shapes the software can ask the user if

he/she wishes to start the shape generation with the initial point at the edge or at the centre. Even the initial position of the wire can be asked from the user to be at 90° or a spline with reference to the home postion.

The present computer needs to be replaced with a faster computer having more memory, so that the calculations and communication between computer/manipulator/WEDM machine can be done in real time. The programming language also needs to be in compiled version to increase the speed of the process.

As it is mentioned in chapter four that each shape generating software is divided into two parts, the geometry description part, and the part which sets machining conditions and controls the manipulator motion. Two major modifications can be done for both of these parts of the programs. Firstly, the shape geometries which are described in three different ways i.e. calculating the co-ordinates, built-in co-ordinates and fed-in co-ordinates through key board, can be fully integrated by describing them through AUTOCAD or some other draughting package. Describing the shape geometry by such package will give greater flexibility and will speed up the process.

The other part of the programs also needs to be improved to monitor the complete WEDM process and to optimize the system performance. This can be done in two

ways. Firstly, all the machining conditions for different kinds of conductive metallic materials can be set on the WEDM machine and then the only parameter required is the selection of the workpiece feedrate for the manipulator to carry out the test. This way a number of geometries can be produced, however, without any adaptive control the process will be quite inefficient. Another way to resolve this problem would involve a number of connections to be made to the PC23 indexer (eg. the micro-switch, which sends the trigger input signal to the micro-computer), which can be dedicated to continuously monitor the different machining parameters and then for correcting these machining conditions the programmable out puts can be sent to the WEDM machine through the interfacing circuits (eg. PVR, which is described in chapter three). The design of the present manipulator can also be modified to suit other non-traditional methods of machining ECM and LBM.

REFERENCES

1. Yoram Koren, "Computer Control of Manufacturing systems.", Kosaido Printing Co., Ltd., Japan. 1983. ISBN. 07-06637-3

2. Michelell P. Groover and Emory W. Zimmer, Jr., " CAD\CAM Computer aided Design and Manufacturing.", Prentice-Hall, New Jersey, America. 1984. ISBN. 0-13-110130-7.

3. Kochhar AK. and Burns N.D., " Microprocessors and their manufacturing applications.", Edward Arnold Ltd. London. 1983 , ISBN 07131 34704.

4. Modern machine shop. NC \ CIM Guide book.Cincinnati, Ohio, Gardner, 1987.

5. Rosenberg j., "A History of Numernical Control 1949 to 1973." DoD DAHC -15-72-C-0308, 1973.

6. Ogden H., " Mechanical Design Aspects of Electronically Controlled Machine Tools.", Proc. 4th Intl. MTDR Conf. 1963 , P. 37, Oxford Pergamon Press 1963.

7. Leathan-Jones B."Introduction to Numerical Control." Pitman., London. 1986.

8. Chao-Hwa Chang, Michel A. Melkanoff., " NC Machine Programming And Software Design."Prentice hall, new Jersey, USA. ISBN 0-13-610809-1, 1989.

9. Koren Y., " Computer Control of Manufacturing Systems.", New York, Mc Graw-Hill, 1983.

10. Pressman R.S. and William J.E." Numerical Control and Computer Aided Manufacturing.", New York. Willey, 1977.

11. Wick C., "Advances in Machining Centers.", Manufacturing Engineering, October 1987., p. 24.

12. Koenigsberger F., " Trends in the Design in the Metal Cutting Machine Tools.", CRIP Annals, Vol.23, No. 2, 1974., P. 255.

13. Drayton D.E., et al, " Automatically Programmed Tools.", Numerical Control Programming Languages, Proc. 1st Intl. IFIP/IFAC PROLAMAT Conf., 1969. Amsterdam: North-Holland, 1970.

14. Shah R., "NC Guide Numerical Control Hand Book", 2nd edition. Zurich, Switzerland. NCA Verlag, 1979.

15. AISI Standard AISI X3-37-1980: Programming Language APT. New YORK American National Standard Institute, 1980.

16. Lang K., et al, " Contribution of Numerical Control to the Development of metal forming processes.", CRIP Annals, Vol. 31, No 2, 1982, P. 511.

17. Thyer G.E., " Computer Numerical Control of Machine Tool.", Heinemann professional publishing., 1988. ISBN. 0434919594.

18. Smith D.N., and Evans L., " Managment Standards for Computer and Numerical Controls.", University of Michigan, Ann Arbor, 1977.

19. Anne Cardoza and Suzee J. VLK., "ROBOTICS." ,Tab Books Inc. America., 1985 , ISBN 0-8306-0858-3.

20. Michael B. Roberts, "Robots in material handling application ", Proc. of 6th Irish Manufacturing Committee, Dublin, Ireland, 1989, P. 1184-1199.

21. Francis N-Nagy Andras Siegler, " Engineering Foundations of Robotics ", Prentice-Hall international London , 1986, ISBN. 0-13-278805-5

22. Clarke H., and N-Nagy F.L., "Powering the electric arm, electric drives ", 1983.

23. N-Nagy F.L. ,"Promoting awareness of industrial application of microprocessors, Electronic and Power.", Vol 26, No.6, 1980.

24. Korein J.U , Ish-Shalom J , "Robotics IBM Systems Journal.", Vol.26, No.1, 1987, P.55-95.

25. Yan J., et al,"Review of Robotics, classifications and applications.", Proc. of 6th Conf. of the Irish Manufacturing Committee, Dublin, 1989, P.1200-1221.

26. Hans B Kief,"Flexible Automation.", Becker publishing company (U.K.) ltd. , 1986, ISBN. 0-9512010-0-X.

27. Roy A.Lindberg, " Processes and materials of manufacture ", third edition, ISBN. 0-205-07888-5. PP.723-743.

28. Snoey R., " Non-Conventional Machining Techniques, The State of the Art.", ASME, The winter annual meeting of ASME Ahaheim, California, USA. VOL 22, 7-12 December 1986, PP. 1-20.

29. Paul DeGarmo E , Black J.Temple and Ronald Kosher, "Meterials and processes in manufacturing.", 7th edition, Collier Macmillan Publishers London, ISBN. 0-02-946140-5, PP. 837-865.

30. Lissaman AJ. and Martin S.J., " Principles of engineering production.", PP.289-333.

31. Kremer D., et al, "The state of the art of ultrasonic machining." Annals of the CRIP, Vol. 30/1/1981. PP.107-110.

32. Vankatesh V.C., "Parametric studies on Abrasive Jet Machining.", Annals of the CRIP , Vol. 33/1/1984, PP. 109-112.

33. Goyer Andy, Moehring Susan, " ECM: little known but very useful.", Modern machine shop, Vol. 6 , No. 11, April 1988, PP.62-69.

34. De Regt C.," ECM for the production of high precision components.", International Symposium on electromachining, ISME-8, Moscow, June 1986.

35. Phillips and Robert E., "What is Electro Chemical Grinding and how does it work.", Non-traditional Machining Conference, Cincinnati, USA, December 2-3 1985, PP. 65-70

36. Rhoades, Lawrence J., "Applying non-traditional Machining Techniques for improved turbine engine design.", ASME, Newyork, America, 4-8 June 1989, PP. 1-9.

37. Dauw D.F., Snoeys R. and Staelens F., "A real time tool wear monitoring function to be used for EDM adaptive control.", ASME, the winter annual meeting of ASME Anaheim, California, USA, Vol. 22, 7-12 December 1986, PP. 21-38.

38. Dauw D.F., Snoeys R., "Adaptive control optimization of the electro discharge machining process by real time pulse detection.", Adv. Manuf. Processes, Vol. 1 , No.1, 1986, PP.45-81.

39. Kruth J.P., Snoeys R. and Van Brussel H., "Adaptive control Optimization of the EDM Process using mini computers.", Computers in industry, North Holland Publishing Co., Vol.1, No.2, 1979, PP.65-75.

40. Kruth J.P. Ir., Snoeys R., Van Brussel H. Ir., "In-Process Optimization of Electro Discharge Machining.", 19th International Machine Tool Design Research Conference, Manchester, Vol.1, No. 2, 1979, PP. 567-574.

41. Tseng M., VanDyck F., Lascoe O.D., "Computerized process parameter selection for EDM of blanking and piercing dies.", 3rd North American metal working research Conference, (NAM RC3)1975, PP. 515-927.

42. McGeough J.A. and Rasmussen H.," A macro scopic model of Electro Discharge Machining.", International J. TOOL Des. RES., Vol. 22, No. 4, 1982, Printed in Britian, PP. 333-339.

43. Hatschek R.L., "EDM update.", American Machinist Special Repot 768, March 1984, PP.113-124.

44. "Pushing the limits of EDM.", American Machinist and Automated Manufacturing, July 1986, PP. 89-91.

45. Muirhead C.M., Gregory M.N., Jones D.W., "Aspark erosion technique for high accuracymetal spheres.", Jorrnal of physics E: scientific instruments Vol 9, No. 10, October 1976, PP. 812-814.

46. "Spark erosion for intricate shapes.", Engineering Digest (U.K.), April 1984, Vol. 45 (4), PP 43-44

47. Elman C. Jameson, "Holes edge condition using EDM.", SME International and Manufacturig Engineering Conference, May 1982.

48. Mark Albert, "EDM close control for a close shave.", Modern Machine Shop 1981.

49. Lief Houman, " Techanical Paper·- Understanding the EDM process and the power supply which controls it." International tool and manufacturing Engineering Conference, Philadelphia USA, MR74-194, 29 April to 3rd May 1974, PP 1-19

50. Gettelman K M , "EDM drills them small.", Modern Machine Shop 1973.

51. Barash M., " Electric Spark Machining.", Int J. Mach. Tool Des. Res , Vol.2, Perganmon Press 1962, PP. 381-295.

52. Quinlan J.C., "Harnessing the spark the revolution in EDM.", Tooling and Production, September 1983, PP. 37-42

53. Ron Piotrowski, "EDM Centres and Convensional CNC EDM.", SME , September 1981.

54. Tseng M.M., " A systematic approach to the adaptive control of the Electro Discharge Machining Process.", Journal of engineering for industry, Vol. 100, August 1978, PP. 303-309.

55. Dauw D.F., Snoeys R. and Dekeyser W., "EDM electrode wear analysis by real time pulse detection.", 11th North American Metal Working Research Conference (NARMC XIth), May 1983, PP. 372-378

56. Snoeys D.W., Dauw D and Jennes M , "Survey of EDM Adaptive Control and Detection systems ", Annals of CRIP Vol. 31, No. 2, 1984, PP.483-489.

57. Snoeys R. and Van Dıjck F., "Physıco Mathematıcal analysıs of the EDM process.", North Amerıcan Metal Workıng Research Conference, May 1973.

58. Bhattacharyya S.K. and M.Kettle, "Some observatıons on spark-erosıon machınıng.", Productıon Engıneer (London), Vol. 51, No.9, September 1972, PP. 305-311.

59. Jeswanı M.L., "Study of surface fınısh ın EDM.", Semı anual paper meetıng Jaıpur Indıa, 13-14 November 1976, JNLO of ınstıtute of engg., mech. Dıv. Indıa., Vol. 57, PT ME-6, May 1977, PP.329-333.

60. Carter G.A. and Jergas I., "Choıce of EDM toolıng.", EDM dıegest, Vol 3, No.2, PP.18-24.

61. Charles Vollaro, "Specıfıcatıon of EDM Dıelectrıc fluıds.", Modern Machıne Shop 1978.

62. Snoeys R., Staelens F and Dauw D., "Adaptıve control Optımızatıon as basıs for ıntellıgent EDM dıe sınkıng machınes.", ASME, the wınter annual meetıng of ASME Anaheım, Calıfornıa, Vol. 22, No 22, December 7-12, 1986, PP 63-78.

63. Nagao Saıto, "Recent EDM technıques ın Japan.", Bull of Japanese Socıety of Precısıon Engıneerıng, Vol. 18, No 2, June 1984, PP. 110-117

64. Snoeys R., Dauw D.F. and Kruth J.P., " Survey ın adaptıve control ın EDM.", Journal of Manufacturıng system, Vol. 2, No. 2, 1983, PP. 147-164.

65. "CNC and Tool Changer Automate EDMs." Tool and productıon August 1981.

66. Konıg W., Jorres L. and Behmer U., "The kınematıcs of planetary Erosıon as a Basıs for Electro Dıscharge Polıshıng and process optımızatıon Strategıes.", ASME, The wınter annual meetıng of ASME Anaheım, Calıfornıa USA, Vol. 22, 7-12 December 1986. PP. 39-50.

67. Hıroshı Konno, Katsuhıro Komuro, Makoto, Tateshı Kıshınamı and Katsumasa Saıto, "Contourıng EDM by Multıple axıs Numerıcal Control.", Proceedıngs of the 5th Internatıonal Conference on Productıon Engıneerıng Tokyo, July 1984, PP. 430-435.

68. Saıto K., Kıshınamı T., Konno H. and Sato M., " Development of Numerıcal Contourıng Control Electrıc Dıschagre Machınıng (NCC-EDM)", Annals of the CRIP, Hıfa, Vol. 35, No. 1, August 1986, PP. 117-120.

69. "EDM speeds Fuel injector production.", Tooling and Production, April 1982.

70. Ken Gettelman, "Travelling Wire EDM Carves Solid Carbide Punches and Dies that Match.", Modern Machine Shop February 1976, PP. 66-73.

71. Walter J. Reed, " Travelling Wire EDM cuts new path in die making.", Machine and Tool Blue Book, April 1976, PP.56-60

72. Siegfried Gruber, " Revolution in Diemaking.", Society of Manufacturing Engineers, August 1975, MR 75-163.

73. Charles Emerson, "Micro Machining to Millionth", American Machinist And Automated Manufacturing, July 1986, PP.89-91.

74. Broatch J.Stewart, "Cutting with a wire.", Society of Manufacturing Engineers, 1977, MR 77-336.

75. Merchant M Eugene, "Computer Integrated Manufacturing as the Basis for the Factory of the Future.", Robotics and Computer Integrated Manufacturing, Vol. 2, No. 2, 1985, PP. 89-99.

76. Erle I. and Shober II., " What Happens in EDM.", Manufacturing Engineering July 1976.

77. Charles Wick, John T. Benedict and Raymond F. Veilleux, "Tool and Manufacturing Engineers Hand Book.", Vol. 1, Machining March 1983.

78. Mark Albert, "Stratified Wire For Travelling Wire/EDM.", Modern Machine Shop May 1981, PP.97-103.

79. Ray Milton, "TW/EDM Makes on Multiple Part-Work ",Modern Machine Shop December 191980, PP. 86-93.

80. Dekeyser W , Snoeys R. and Jennes M., "A thermal model to investigate the wire rupture phenomenon for improving performance in EDM Wire cutting ", Journal of Manufacturing Systems, Vol 4, No. 2, 1985, PP. 179-190.

81. Dave Dulebohn, " A Look at Wire EDM.", Manufacturing Engineering, March 1979, PP. 58-63.

82. Harry Kern," User Benefits from improved Wire EDM.", Tool and Production, March 1978. Vol. 43, No. 12, PP. 72-73.

83. Nickols I , "Wire EDM is Making it's Move.", Machinary and Production Eng., Vol 132, No. 3418, 5th July 1978, PP.22-23.

84. Fischi and Fuhrmann, "New Possibilities With the 3-D tapper cutting device on EDM.", SAFR Mach Tool Rev., Vol. 16, No. 4, April 1973, PP. 5-7.

85. Kazuhiko Kobayashi and Tamio Takawashi, " EDM For Die Making.", Mitsubishi Electric Advance (Japan), Vol. 28, Sept 1984, PP. 10-13

86. Kinoshita N., Fukui M and Gamo G , " Control of Wire EDM Preventing electrode from Breaking.", Annals of CRIP, Vol. 31/1/1982. PP. 111-114.

87. Jennes M., Snoeys R., Dekeyser, " Comparisions of various approaches to model the thermal loadon the EDM Wire Electrode.", Annals of CRIP Vol. 33/1/1984. PP. 93-98

88. Dauw D., Snoeys R , "Adaptive control of EDM process by real time pulse detection." International Conference of the Manufacturing Science and Technology of the Future, M I.T., USA. International Journal of Robotics and Computer Integrated Manufacturing, 9-12 October 1984.

89. Snoeys R., Dauw D. and Kruth J., "Survey of Adaptive Control in EDM.",Journal of Manufacturing Systems, Volume 2, No 2, 1983, PP.147-164.

90. Tanimura T., Heuvelman C J. and Veenstra P.C., "The properties of the Servo Gap Sensor with Wire Spark Erosion Machining.", Annals of CRIP, Vol. 25/1 , 1977, PP. 59-63

91. Bernd M. Schumacher, "Precision EDMing with Multiple Conicity Potential.", EDM Digest, Vol IV, No. 1, PP 8-17.

92. Takamasa Daimaru, "A Wire cut EDM System with conversational APT ", Mitsubishi Electric Advance, March 1989.

93. Brocher of AGIE Corporation.

94. Jennes M. and Snoeyes R., " Adaptive control of EDM wire cutting based on pulse analysis.", International Symposium for Electro-machining, ISME Moscow 1986.

95. Compumotor Operator's manual, PC-23, P/N: 88-007015-03, Parker Hannifin Corporation, Compumotor division, USA

96. Compumotor operator's manual, KS-drive Bulletin OM-8200-KS-DRIVE P/N: 88-007042-014, Parker Hannifin Corporation, Compumotor division, USA.

97. General Catalog of "Compumotor Programmable motion control." 1987, Parker - Hannifin Corporation.

98. L.C.   MOTT,"Engineering Drawing and Construction.",
    Second edition , Oxford University press,   1976, ISBN
    0 198591144, 1976, PP. 195-199.

BIBLIOGRAPHY

1. Natsuo Kinoshita, Al, "A Fundamental Study for Improving the Performance of WEDM.", presented at SME 1980. Western Metal & Tool Conference and exposition, March 1980.

2. Tomalin, Dan, "Better Wire: Lowers EDM Costs.", Modern Machine Shop VOL. 61, No.11, April. 1989, P.66-71.

3. Y.H. Huang, Al, "The Identification and it's Means of Servo feed Adaptive Control System in WEDM.", CRIP Annals 1986, Manufacturing Technology. Annals of the International Institute for Production Engineering Research Jerusalem-Hifa ISR. 17-22 Aug. 1986, P.121-123.

4. A.C.M. Daniels, Phillips, Eindhoven, "NC Wire Spark Erosion --- A Survey.", Annals of the CRIP Vol 25/2/1976, P 521-525.

5. N. Kinoshita, Al, " "Study on EDM With Wire Electrode; Gap Phenomena.", Annals of The CRIP, 1976, Vol.25(1), P.141, ET SEQ.

6. B. M. Bikhman et Al, "Selection of Process Parameters for EDM Wire Cutting Machines and Tooling.", Vol. 48, No 10, 1977, P.27-27.

7. Spur. G., Al, "Wire EDM of PCD.", Industrial Diamond Review, Vol.48, No.529, June 1988, P.264-266.

8. F.N.G. Ayres, "An Electro-Chemical Machining Demonstration Facility.", International Journal of Applied Engg. Education., Vol 3, No.1, 1987, P 59-67.

9. A R. Mileham and S.J.Harvey, "Avoidance of Macro-Surface Defects in Electro-Chemical Machining (ECM) of Steel Workpieces.", Proceedings of the First National Conference on Production., Research Uni. of Nottingham, Sept 1985, P.374-380.

10. S.S. Grewal and P.W.Jackson, "Electro-Chemical Machining of Orthopaedic Components.", Proceedings of the First National Conference on Production Research , Uni. of Nottingham, Sept. 1985, P.366-373.

11. Risko, Donald G., "ECM/EDM Process of Die and Mold Production.", 2nd Biennial International Machine Tool Technical Conf. Rosemont, iL, USA. 5-13 Sept. 1984, P.9-131 TO 9-139.

12. V.P. Smolentsev, Al, "Electro-Chemically Production of Small Diameter Holes in Dielectrics.", Soviet Surface Engineering and Applied Electro-Chemistry No.6 , 1987, P.106-111.

13   Aaron, Truman E., "Evaluation and Selection of Parts for ECM.", 2nd Biennial International Machine Tool Technical Conference, Rosemont, Il, USA. 5-13 Sept. 1984, P.9-141 to 9-146.

14. H. Tsuchiya., Al, "WECM of Glasses and Ceramics.", Proceedings of 5th International Conference on Production Engineering, Tokyo, 9-11 July 1984, P.413-417.

15. Cauthor Kunio Chikamori, Al, "Wire ECM With Pulse Current.", Proceedings of 5th International Conference on Production Engineering, Tokyo, 9-11 July 1984, P.407-412.

16. Kirpa Shanker and A.Ghosh, "A Study of Electro-Spark Machining Characteristic with Electro-Magnetic Spark Gap Controling Mechanism.", Int. Jour. Mach Tool. Des. Res., Vol.15, Pergamon Press 1975, P.209-221.

17. K. Przyklenk, "Abrasive Flow Machining - A Process for Surface Finishing and Deburring of Workpieces With a Complicated Shape by Means of an Abrasive Laden Medium." ASME, The Winter Annual Meeting of ASME Anaheim, California, December 7-12, 1986, Vol. 22, P.101,110.

18. J.R. Crppkall, Al, "An Analysis of EDM Utilisation in Industrial Tooling Manufacture.", Annals of The CRIP Vol.27, NO.1, 1978.

19. R.F. Cooke And J R. Crookall, "An Investigation of Some Statical Aspects of Electro-Discharge Machining.", Int. Journl. Mach. Tool. Des. Res. Vol.13, Pergamon Press 1973, P.271-286.

20. C. Frei, Al, "A New Approch For Contamination Measurements For EDM Dielectrics.", CRIP Annals, Vol.36, No 1, 1987, P.111-113

21. J.R. Crookal, "A Basic Analysis of Pulse Trains in Electro-Discharge Machining.", Int. Jour Mach. Tool Des. Res. Vol.13, Pergamon Press 1973, P.199-213

22. Dr. Om Johari, "A Close Look at Surface Finish.", Sof: Jnlo. of Institute of BNA (India), Mech. Eng Div, M.L. Jeswani, American Machinist,1969 Vol.113(24), P.92-96 SEQ.

23. B.A. Bakewell, T.H. Lee, B.F.Scott., "Assignment of Holes Drilled by Laser Beam.", Conference on Electrical Methods of Machining, Forming & Coating, London WC2, 18-20 Nov. 1975, P.258-264.

24. Nagao Saito, Kazuhiko Kobayashi, "Adaptive Control of EDM.", Mitsubishi Denki Eng (Japan), Dec.1970, No.27, P.39.

25. S. Derholm, "Control System Puts EDM Cut Through Self-Correction Sequence.", Design News, 5th July 1971, Vol.26, NO 13.

26. A.T. Kravets, A.F.Bogachev, "Computer Controlled NC EDM Sections.", Soviet Engineering Research, Vol.65, Issue 4, 1985, P.40.

27. M.Motoki and K.Hashiguchi, "Energy Distribution at the Gap in Electric Discharge Machining.", Annals of CRIP, Presented in Great Britain 1967, Vol. XIV, P.485-489.

28. Atkey Martin, "Electro-Machining Can Eat in to Costs.", Working Production Vol.121, No.8, August 1977, P.43-45

29. J.E. Greenge and J.L. Guerrero-alvarez, "Electro Erosion of Metal Surfaces.", Metallurgical Transactions Vol 5, No.3, March 1974, P. 695-706

30. J.R.Crookall, and B.Khor, "Electro-Discharge Machined Surfaces ", 15th Int. MTDR Conference, Birmingham 1974, P.373-384

31. N.H. Cook, Al, "Experimental Studies in Electro-Machining ", Amrican Society of Mechanical Engineers No.72-WA/PROD-21 For Meet. Nov. 26-30, 1972, P.1-6.

32. H.E. De Bruijn, Al, "Effect of a Magnet Field of the Gap Cleaning in EDM.", Institute for Production Engineering 28 General Assembly 783- 2500 Eindhoven. The Netherlands 28-30 Augst 1978.

33. Kiyoshi Inoue, "EDM Parameter Control System.", U.S. Patent 3875374 USA.,1st April 1975, P.1-16.

34. T.W. Shaw, "Electronic Circuit Techniques in EDM.", Conference on Electrical Methods of Machining, Forming & Coating, 18-20 Nov 1975, London. P 140-146

35. Malcolm Whitmore, "EDM in Aircraft Industry.", Aircraft Engg·, April 1984

36. C.S. Kahlon, H.J. Baker, C.F Noble and F.Koenigsberger, "Electric Spark Toughening of Cutting Tools and Steel components.", Int. Jour. Mach. Tool Des. Res., Pergonmon Press, Vol.10, P.95-121.

37. E.C Jameson, "EDM Methods of Production Small Holes.", Presented at The SME 1981 International Tool & Manufacturing Engg. Conference, 1981.

38. Simo H Laurila, "First Order Position by 3-D EDM.", Surveying & Maping ,Vol. 45 No.2, P.145-151.

39. Yasunori Kurahashi, "FA Technology For EDMs.", Mitsubishi Electric Advance Vol.46, March 89, P.22-24.

40. K.P. Rajurkar, Al, "Formation and Ejection of EDM Debris.", ASME Technocal Conference, Miami USA. 17-22 Nov. 1985.

41. L.D. Fiel, L.A. Waits, "Graphite as an EDM Electrode Material.", Poco Graphite, Inc., 1601 S. State Street, Decatur, Texas 76234, July 1986, P.831-832.

42. J. Steffen, "High Precision Laser Machining.", Conference on Electrical Methods of Machining, Forming & Coating, London WC2, 18-20 Nov. 1975, P 283-290.

43. Mark Albert, "How CNC Changed in EDM.", Modern Machine Shop, Oct 1982, P.53-60.

44. D. Dauw, Al, "High Speed Pulse Discrimination For Real Time EDM Analysis Electro-Machining ", Proceedings of the 7th International Symposium. 12-14 April 1983, P.9-20.

45. H.E. De Bruyn, "Has The Time Delay Influence on The EDM process.", Annals of the CRIP 1982 Belgium , 1982, P.103-106.

46. R. Snoeys, D.Dauw, J.P.Kruth, "Improved Adaptive Control System for EDM process.", Annals of CRIP (SWIZ), 1980, VOL. 29, No.1, P.97-101.

47. C.J. Heuvelman, "Ignition Delay as a Sensor for The Electro-Discharge Machining Servo Mechanism.", Proc. Int. Conf on Production Engg. Tokyo, 1974, P.38-41.

48. S.K. Bhattacharyya, M F Menshawy, El, "Monitoring and Controlling the EDM Process.", Journal of Engineering for Industry, Agst. 1980, Vol.102, P.189-194.

49. D.C. Roy and P K. Mishra, "Removal Rate in Abrasive Jet Machining- AN Elasto-Plastic Model.", ASME, The Winter Annual Meeting of ASME Anaheim, California, December 7-12, 1986, Vol. 22, P. 111-118.

50. S.K. Bhattacharyya., Al, "Monitoring the EDM Process By Radio Signals ", International Journal of Production Research Vol.16, No.5, Sept. 1978, P.353-363.

51. H. Rhyner, "Recent Development in EDM Monitor and Control Systems Conference on Electrical Methods of Machining Forming and Coating ", 18-20 Nov. 1975. London, P.132-140

52. I. Miyamoto and K. Kawata, "Surface Finish of Steel a Guage Block With low Energy Ion beams.", ASME, The Winter Annual Meeting of ASME Anaheim, California, December 7-12, 1986, Vol. 22, P.1-20.

53. Kell Lock, Brian, "Spark Erosion Cell Cuts Blade Times.", Machinery & Prosuction Engineering Vol.144, No.3694, May 1986, P.46-421.

54. Karl Heinz, Al, "Spark Erosion of Cold Mill Roll Surfaces.", Metallurgical Plant & Technology (MPT), Vol.10, No.2, 1987, P.72-72.

55. C.H. Kahng, Al, "Surface Characteristics Behaviour Due to Rough and Fine Cutting by EDM.", (CRIP) Conference & General Assembly New Delhi India, 29-31 August 1977, P.77-82.

56. S.D. Azarov, "Spark Erosion Machining of Intricate Working Surfaces in Cast Waterford dies.", Sov. Cast Tech. No.6, 1986, P.35-36

57. Prof. Radhakirshnan, B.T. Achyutha, "Study of Surface Formed in EDM Using Relocation Techniques.", Jour. Inst. Engineering (India), May1980, Vol.60, PT ME6, P.217-222.

58. P.W. Wells and P.C.T. Willey, "The Effect of Variation in Die Electric Flow Rate in the Gap on Wear Ratio and Surface Finish During Electro-Discharges.", Conference on Electrical Methods of Machining, Forming & Coating, London WC2, 18-20 Nov. 1975, P 110-117.

59. Al Rosen, "Techanical Paper:- Small Steps to Big Savings With ECM-(AN OLD FRIEND WITH A NEW NAME).", Paprs Presented at the SAE 23rd Annual Aerospace / Aeroline Plating & Metal Finishing Forum & Exposition. 16-19 Feb. 87

60. Leif Houman, Eltee Pulisitron, "Techanical Paper:- Time Estimate of EDM Jobs.", Westren Tool & Metal Conference Exposition Los Angles, 14-17 March 1977.

61. Richard T. Benger, Al, "Techanical Paper:- EDM and the Die Designer.", New England Engineering Conference, Boston, 10-12 Oct. 1973, Society of Manufacturing Engineers.

62. R.L. Finicle, Al, "Techanical Paper:- Graphite EDM Electride Performance as Affected by Power Supply Variables.", International Tool Exposition Engineering Conference Detroit, 7-11 May 1973, Society of Manufacturing Engineers

63. Leif Howman, Al, "Techanical Paper·- Multi-lead as Used For Production EDM.", Western Metal & Tool Exposition & Conference, Los Angeles California, 8-11 March 1976. Society of Manuf. engineers.

64. Leif Houman, "Techanical Paper:- What's New in EDM Power Supplies and machines.", New England Engineering Conference Boston, 10-12 Oct. 1973. Society of Manufacturing Engineers.

65. J.E. Bannard, P.J. Boden and P.A. Brook, "The Workpiece / Electrolyte Interaction During Electro-Chemical Machining.", Conference on Electrical Methods of Machining, Forming & Coating, London WC2, 18-20 Nov. 1975, P.147-153.

66. H. Cornelissen, Al, "Technological Surfaces an Objective Criterian for Comparing EDM Systems.", Institution for Production Engineering 28 General Assembly 783 2500 Eindhaven. The Netherlands 28-30 August 1978, P.101-106.

67. Glenn C. Hartwig, "Three New Developments in EDM.", Manufacturing Engineering, Dec. 1981, P.66-68.

68. G.V. Smith, "The Level of Development in EDM in 1975.", Procs. Conf. on Electrical Methods of Machining, Forming an Coating London, Nov. 1975, P.101-109.

69. C.J. Heuvelman, R Jansen, J. Van Lierop, G. Theuws, "The Appilication of Micro-Computers in Controlling the Sparking Erosion Process." ISEM 6, June 17-20,1980, P.103-106

70. C.F. Noble and Y.S. Wong, "Use of Micro-Computer Based Instrumentation for the Investigation of EDM With Orbital Tool Movement ", ASME, The Winter Annual Meeting of ASME Anaheim, California, December 7-12, 1986, Vol. 22, P.79-100.