ABSTRACT

FLEXIBLE MANUFACTURING SYSTEM UTILIZING COMPUTER INTEGRATED CONTROL AND MODELING

by

Yahia Mohammed Al-Smadi

In today's fast-automated production, Flexible Manufacturing Systems (FMS) play a very important role by processing a variety of different types of workpieces simultaneously. This study provides valuable information about existing FMS workcells and brings to light a unique concept called Programmable Automation.

Another integrated concept of programmable automation that is discussed is the use of two feasibility approaches towards modeling and controlling FMS operations; the most commonly used is programmable logic controllers (PLC), and the other one, which has not yet implemented in many industrial applications is Petri Net controllers (PN). This latter method is a unique powerful technique to study and analyze any production line or any facility, and it can be used in many other applications of automatic control.

Programmable Automation uses a processor in conventional metal working machines to perform certain tasks through program instructions. Drilling, milling and chamfering machines are good examples for such automation.

Keeping the above issues in concern; this research focuses on other core components that are used in the FMS workcell at New Jersey Institute of Technology, such as; industrial robots, material handling system and finally computer vision.

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by

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This thesis is dedicated to my

beloved parents and family members

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CHAPTER 1

FLEXIBLE MANUFACTURING SYSTEMS

1.1 Introduction

Automation is a technology concerned with the application of mechanical, electronic, and computer based systems used to operate and control production systems. One of the most important types of automation is flexible automation.

Productivity, cost, quality, and utilization are concepts of concern in most industries. Flexible manufacturing systems (FMS) can promote the integration of these concepts and many more which are important to the manufacturer, for example:[27]

- Flexibility.
- Group technology.
- CNC machine tools.
- Automated material handling between machines.
- Computer control of machines.

Flexible manufacturing system can be defined as follows:

A Flexible manufacturing system consists of a group of processing stations (predominantly CNC machine tools), interconnected by means of an automated material handling and storage system, and controlled by an integrated computer system.[27]

In addition a flexible manufacturing system can be defined as a computer controlled configuration of semi-independent work stations and a material handling system designed to efficiently manufacture more than one part number at low to medium volumes.[32]

In this Chapter, the focus will be on data flow and hierarchy of FMS in Sections 1.2 and 1.3 respectively; components of FMS in Section 1.4; facility layout in Section 1.5; and product cycle in Section 1.6.

1.2 Data Flow of FMS

It is important to analyze the data flow of the system and to define the function of each module in the system. The operation of an FMS can be treated as a sequence of events, which can be done concurrently or in series, whereby one event can trigger the occurrence of another event.

It can be seen from the Figure 1.1 how the data flow between elements contributes in FMS and also it can be noted that the response of the system is:

- ✓ Retrieving a new work piece from a storage place
- ✓ Loading/unloading a work piece a robot
- ✓ Loading/unloading tools to the machines by robots
- ✓ Accepting/rejecting machined parts during the inspection stage
- ✓ Controlling the fixtures and clamps
- ✓ Controlling the material handling systems such as carts, transporters, and AGV's
- ✓ Monitoring the conditions of the machine and cutting tool to save the machine from damage.

The system takes care of all procedures until all operations are finished according to the production schedule.

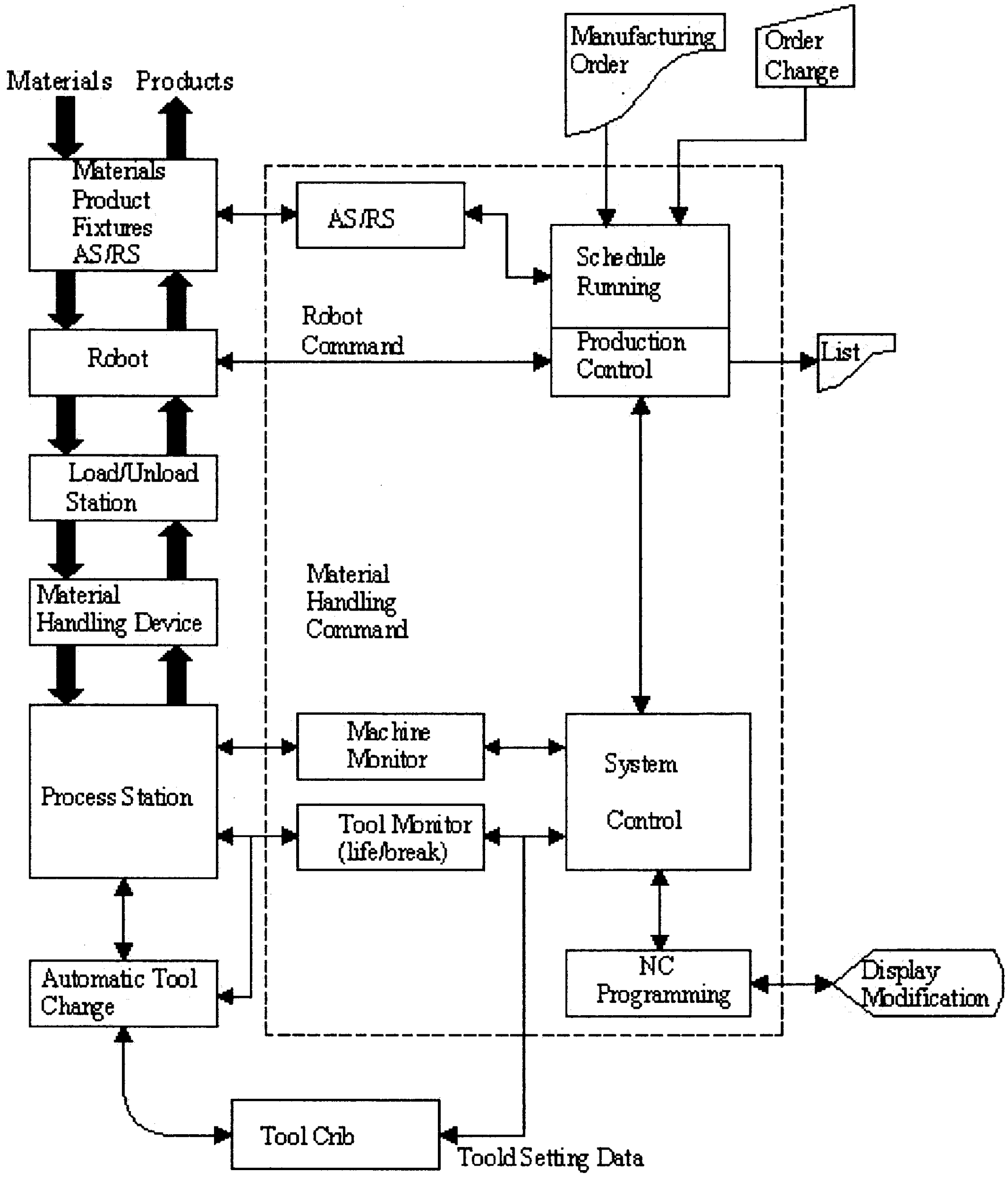


Figure 1.1 Data flow of FMS.

1.3 Hierarchical Structure of an FMS Control System

Typically, the computer control of an FMS is complicated and the way to understand such a control system is to determine how it is designed and then investigate its hierarchical structure. Figure 1.2 is an example that gives a comprehensive understanding of how such systems work. There are three levels which are shown; the higher level contains the host computer, the middle one contains the client computers and the lower level contains all the devices controlled by the clients such as CNC controller, material handling system controller, controller for AS/RS, vision controller, robot controller. In addition, the functions performed within the FMS hierarchy are shown in Figure 1.3. In this figure there is a business computer, which is not primary level, and its basic function is to record and schedule the production and it can be separate. The functions of other components shown in figure below are shown in Figure 1.3.

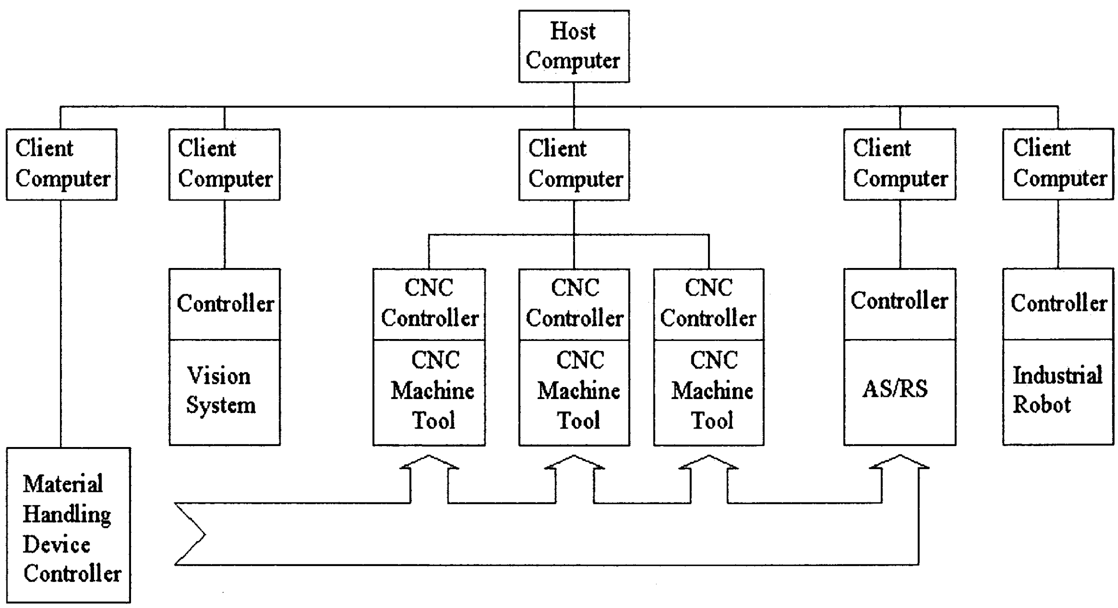


Figure 1.2 Hierarchical structure of FMS.

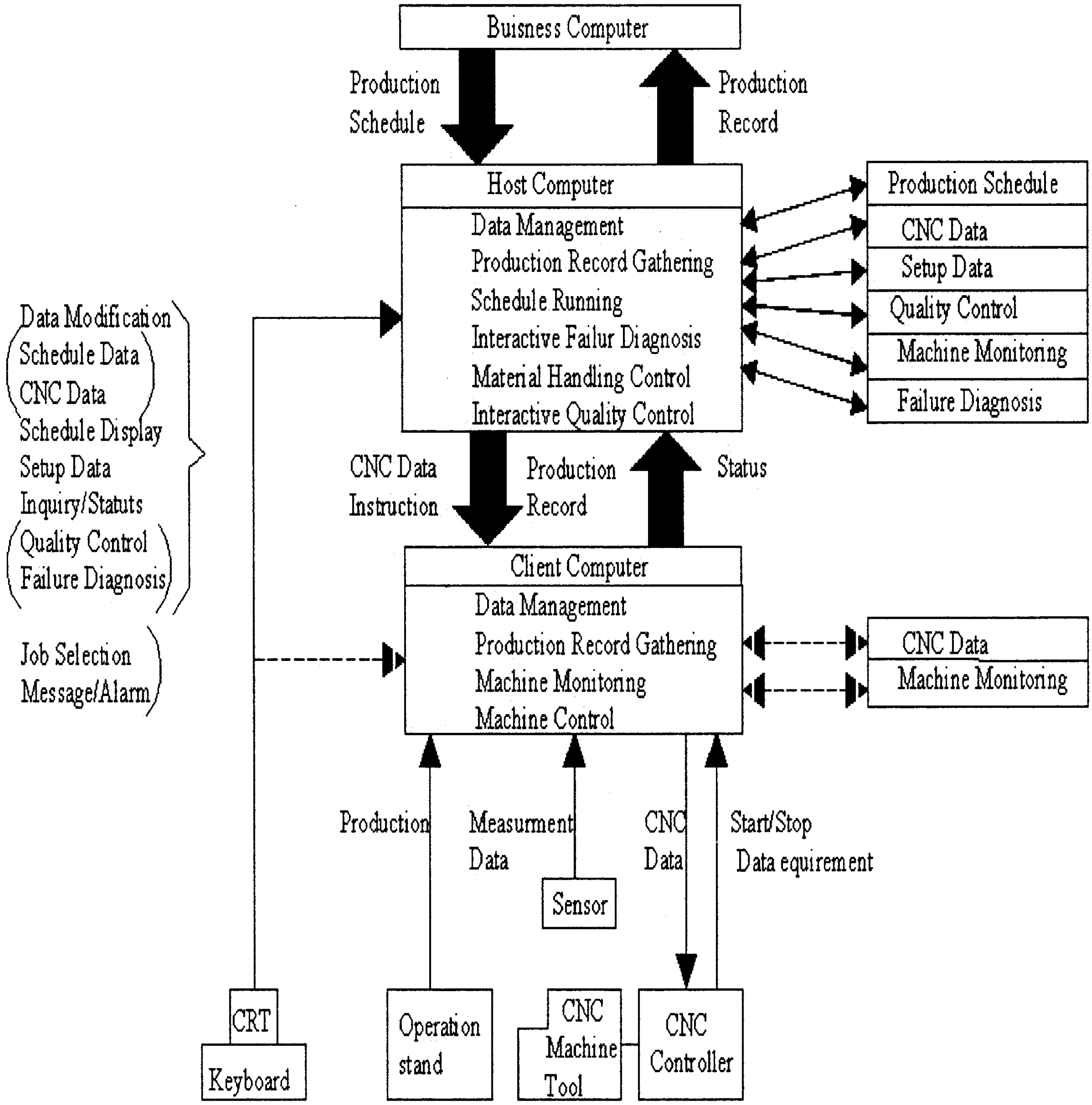


Figure 1.3 Functions performed within the FMS hierarchy.

1.4 Advantages of FMS

The advantages resulting from the implementation of FMS have been studied extensively. They can be summarized as follows:[27&35]

- ✓ Reduced labor cost.

- ✓ Increased output.
- ✓ Decreased manufacturing cost.
- ✓ Increased flexibility.
- ✓ Reduced lead time.

Table 1.1 shows the comparison between conventional manufacturing technology and FMS under three criteria's (optimistic, most likely, and pessimistic).

Table 1.1 Comparison Between FMS and Conventional System Performance

Parameter	Conventional system performance	FMS performance		
		Pessimistic	Most likely	Optimistic
Percentage of machine time spent without part	50	35	20	5
Percentage of time when the part is not being worked on while machine is on	70	35	21	7
Percentage of manufacturing lead time the part spends in moving or waiting	95	92.5	90	85

it can be seen in the table above that in all cases the FMS systems has better performance than conventional systems.

1.5 Components of FMS

In this chapter the focus will be on the analysis of an FMS, which was designed, developed, fabricated and programmed at the New Jersey Institute of Technology (NJIT). The major components included in the FMS are:

1. Processing Stations
2. Industrial Robots
3. Material Handling System

4. Control System

The components of the NJIT FMS cell are shown in Figure 1.4.

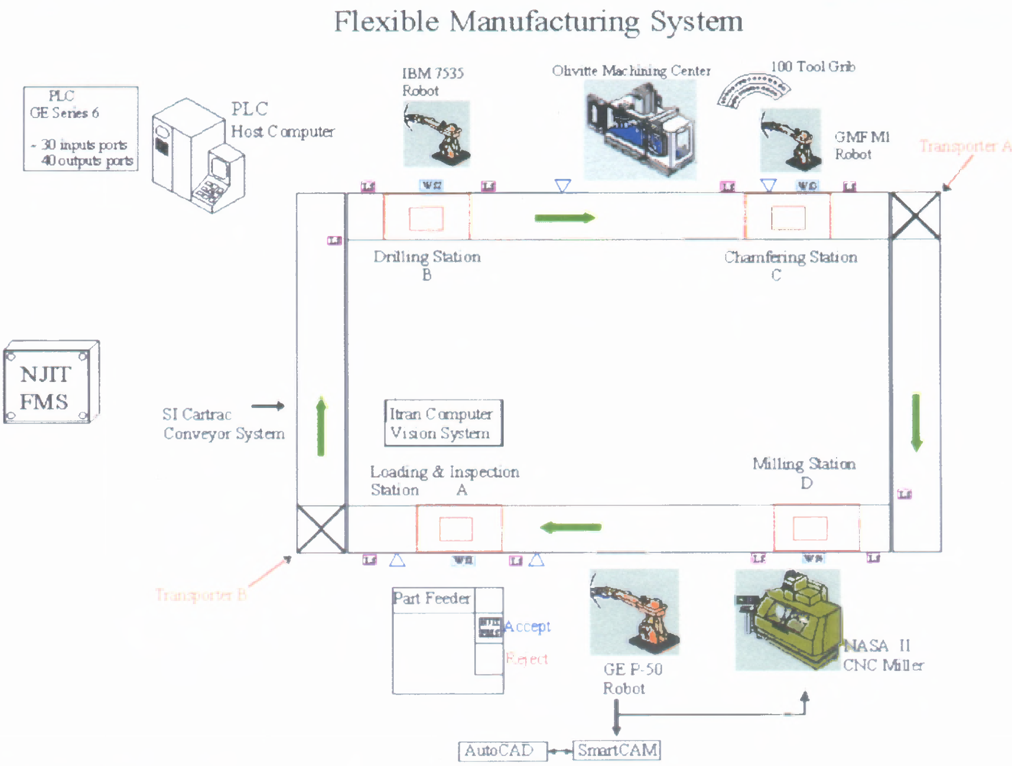


Figure 1.4 FMS components.

1.5.1 Processing Stations.

- CNC Milling Process Station

The NASA II CNC milling machine shown in Figure 1.5, is driven by DC servomotors with a closed loop control system with a 3-axis control motion system. It has the capability to travel in the X, Y, and Z directions, with variations of spindle speed.

Figure 1.5 NASA II CNC milling machine.

- CNC Chamfering Process Station.

The Olivetti Machining station, which is shown Figure 1.6, is serviced by a GMF M1 robot and a carousel of 100 tools.

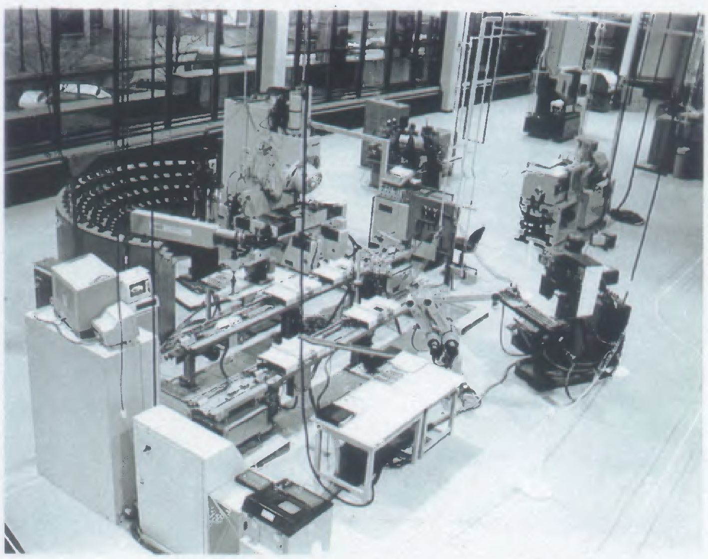


Figure 1.6 Olivetti machining center.Drilling Process Station.

The IBM 7535 Robot uses a drilling end effector. It is shown in Figure 1.7.

Figure 1.7 IBM 7535 robot.

- Vision System

This is a high speed, sophisticated unit programmed by using VPL (vision planning language). The software used to control this system is SensorEdit v2.1c, with many menus to help the user to get the best control of inspection. It is shown in Figure 1.8 with the whole set contained in this system. The Itran computerized vision system inspects the part and decides if the part meets the specifications of the control algorithms. A signal is sent to the PLC in a special format so that the robot can be ordered to place the part in the acceptance or rejection bin.[22]

Figure 1.8 ITRAN Computer vision system.

1.5.2 Robots

- IBM 7535 Robot

This robot is a SCARA type point-to-point robot that is interfaced with the FMS using a photoelectric sensor fixed to the conveyor system. Its specifications are 5 degrees of freedom, 4-axis control, payload up to 30 pounds, and repeatability of 0.005" with DC servo drive. Its configuration is shown in Figure 1.9

Figure 1.9 IBM 7535 robot.

- General Electric P-50 Robot

The specifications of this robot are 5 degrees of freedom, 5-axis robot, payload of up to 22 pounds and repeatability of 0.008". It is used in the automobile industry for spot welding applications and is used in this FMS as a material handling robot with hydraulic drive and a jointed-arm configuration. Figure 1.10 below shows the GE P-50 robot.

Figure 1.10 General Electric P-50 robot.

- GMF M1 Robot

The GMF M1 robot specifications are; 6 degrees of freedom, 4-axis robot, payload up to 44 pounds, repeatability of ± 0.005", DC servo drive, used for palletizing, and its configuration is cylindrical. Figure1.11 shows the GMF M1 robot.

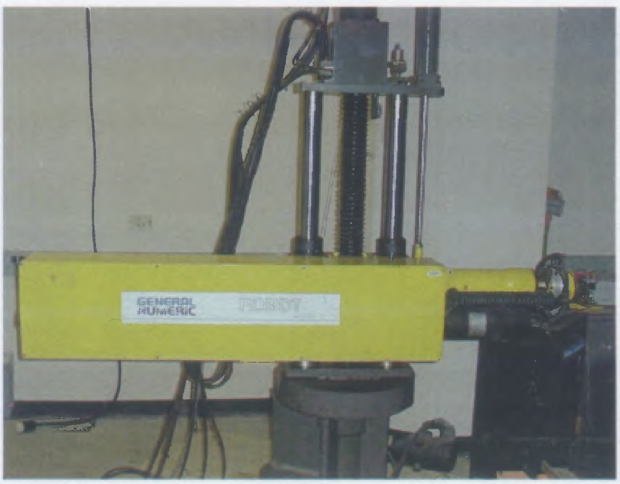


Figure 1.11 GMF M1 robot.

1.5.3 Material Handling and Storage System

The function of the material handling system is to provide convenient access for loading and unloading workparts and should be compatible with the PLC computer control. Figure 1.12 shows the Cartrac material handling system

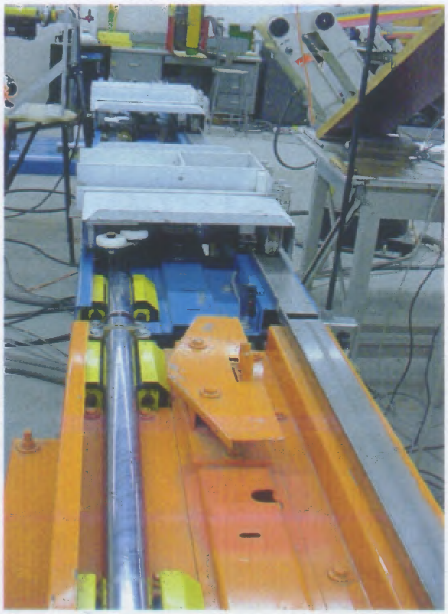


Figure 1.12 Cartrac material handling system.

The type of conveyor used in this system is cart-on-track, it is shown in Figure 1.13. The cart rides on a two-railed track contained in a frame that places the track a few feet above floor level. The carts are not individually powered; instead, they are driven by means of rotating tubes that run between the two rails. A drive wheel, attached to the bottom of the cart and set at an angle to the rotating tube, rests against it and drives the cart forward. Here regulating the angle of contact between the drive wheel and the spinning tube controls the cart speed. When the drive wheel is perpendicular to the tube, the cart doesn't move, as the angle is increased toward 45º, the speed increases. In this way the carts can achieve relatively good accuracies of position.[27]

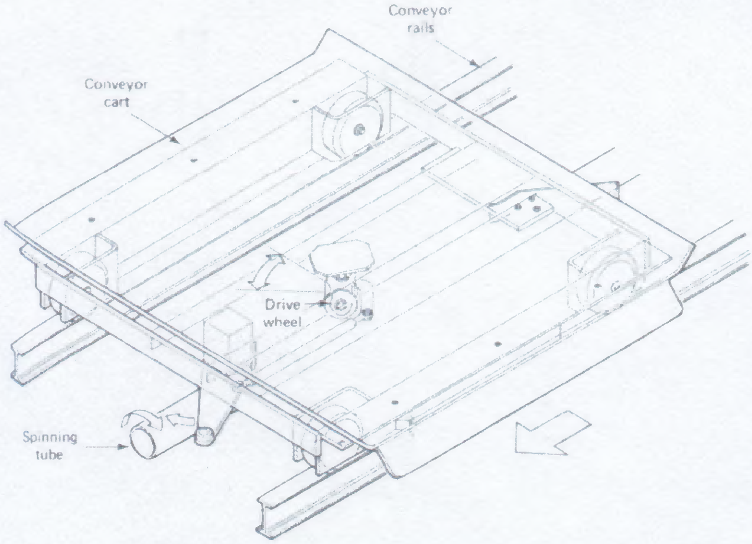


Figure 1.13 Operation of cart-on-track conveyor.

1.5.4 PLC Logic Controller – GE Series Cell Controller

The PLC is the traffic and activities coordinator for the FMS cell. It controls all operations and functions of the processing stations and the material handling system. It is responsible for carts flow control, tool and production control and all the other control activities of the workcell. The subsystem is shown in Figure 1.14.

Figure 1.14 Control system used in NJIT FMS.

1.6 FMS Layout Configuration

The layout of the NJIT FMS has a loop configuration, as it was shown in Figure 1.4 and illustrated in Figure 1.15.additional views for NJIT FMS wrokcell are shown in appendix A. The parts flow in one direction around the loop with the capability to stop at any station.

Figure 1.15 NJIT FMS layout.

1.7 Product Cycle

One complete product cycle for the FMS workcell operates as follows:

•The GE P-50 robot loads the four conveyor carts with blank parts.

•The conveyor carts are indexed to the four process stations by the Cartrac material handling system.

•Each process station performs its function concurrently.

•Each part is indexed to the next process station.

•The IBM 7535 robot is programmed to execute the drilling operation on the part

•The GMF M1 robot picks the part and loads the Olivetti machining center for the chamfering operation.

•The GMF M1 robot also loads the tools from the 100-tool crib into the machining center.

•The GE P-50 robot picks up the part with its vacuum end effecter and places it into the fixture installed on the CNC milling machine.

•The NASA II CNC milling machine performs the etching of 'NJIT FMS' on the upper surface of the part.

•The GE P-50 robot picks up the completed part from the milling machine and loads it back onto the fixture on the cart.

•The Vision system inspects the completed part to determine the acceptance or rejection of the part.

•The GE P-50 robot then picks up the completed part and places it in the acceptance or rejection bin.

CHAPTER 2

COMPUTER NUMERICAL CONTROL

2.1 Introduction

The evolution of this field could not have been possible without the existence and availability of computers, especially mini or personal computers. The most important application of computers was in the development of the control operations in the conventional machines industry such as cutting, welding, lathing, and milling. Computer use in metalworking machines aids in controlling and performing complex and precise machining operations at a low cost.

Sections 2.2, and 2.3 contain CNC classifications, Section 2.4 discusses numerical control (NC), CNC and direct numerical control (DNC), Section 2.5 shows details about NC part programming and Section 2.6 describes some data used in CNC programming. Finally there are examples for CNC programming for the case study in NJIT FMS presented in Section 2.7.

The following terms are used CNC operations:[27]

- Control Resolution: the capability of machine control unit MCU to divide the range of a given axis movement into closely spaced points that can be identified by the controller.
- Accuracy:.the capacity of MCU to position the worktable at a desired location.
- Repeatability: the ability of the control system to return to a given location that was previously programmed into the controller.
- Mechanical Errors: results from gear backlash, leadscrew play, deflection of

machine components, and similar inaccuracies in the mechanical positioning system.

2.2 CNC Machine Classification

CNC machines can be classified as shown in Figure 2.1 according to:

- ✓ Mechanical systems
- ✓ Control systems
- ✓ Coordinate system
- ✓ Motion control
- ✓ Number of axes
- ✓ Control loop system

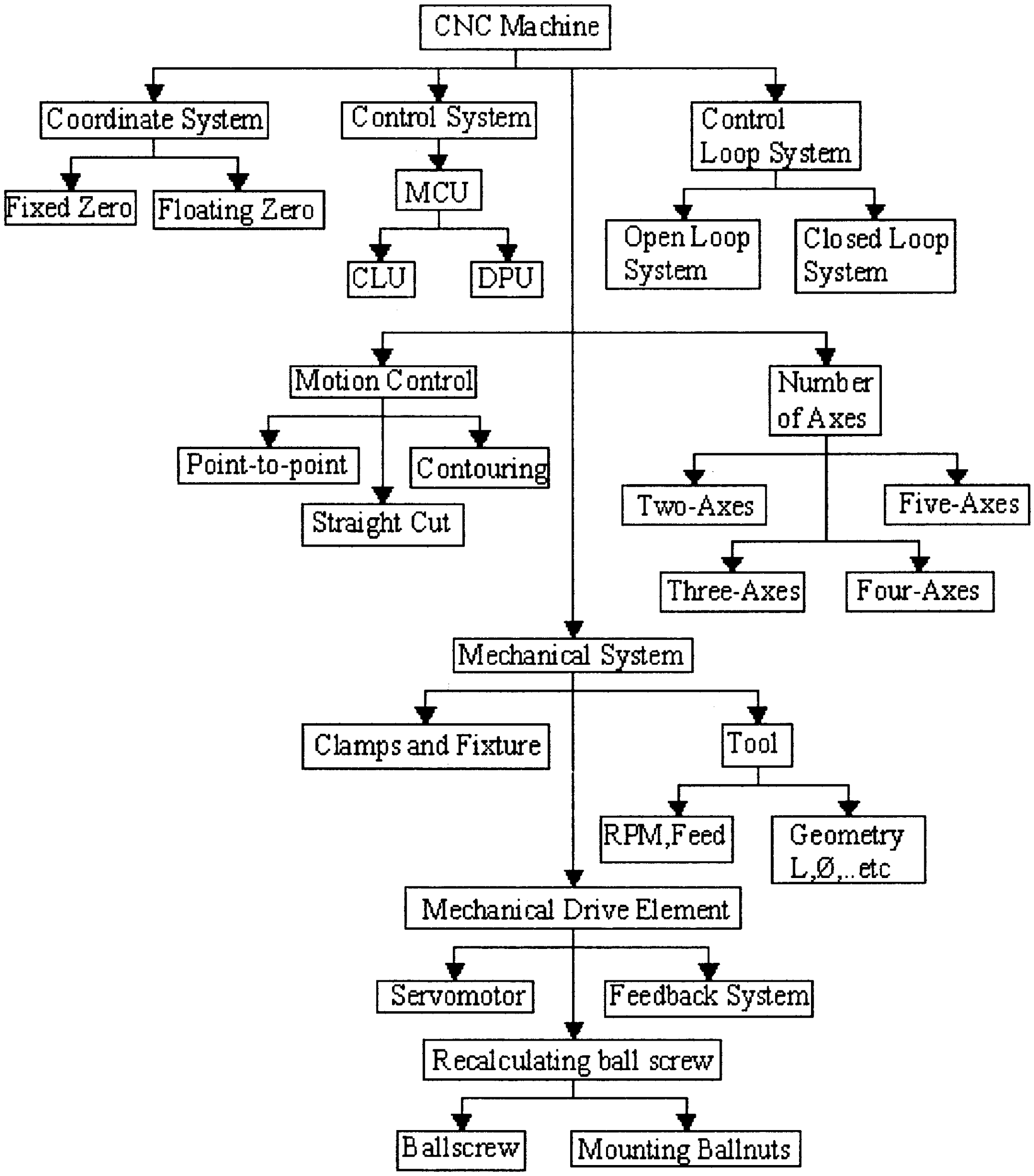


Figure 2.1 Classification of CNC machine

2.2.1 Mechanical Systems

The mechanical system used in CNC machines consists of the following vital parts:

- **Clamps and Fixture:** A Riveted fixture is used in CNC milling table; it is two Perpendicular plates are fixed with rivets or threaded by screws. It's very important to be precise in firming the fixture, so a hydraulic motor is used to push the block to the clamps. Generally, the setup of the fixture is the most time consuming process, which requires tool- making skills to design the proper features for ultimate matching stability.

- **Mechanical Drive Elements** Consist of a servomotor, a feedback system and recalculating ball screws(consisting of ballscrews and a mounting ballnut).

Servomotor

A servomotor shown in Figure 2.2 is an electromechanical device in which electrical input determines the position of the armature of a motor and the rotation of the shaft moves the table forward or backward. They are used extensively in robotics and radio-controlled cars, CNC machines, airplanes, and boats.

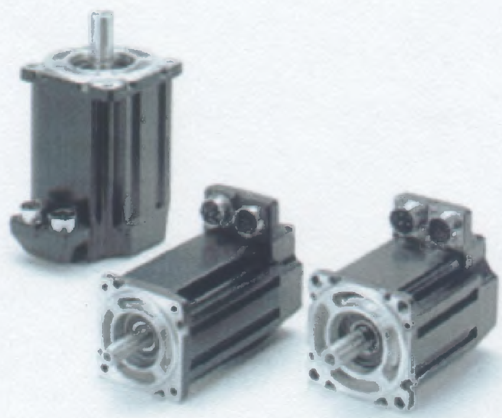
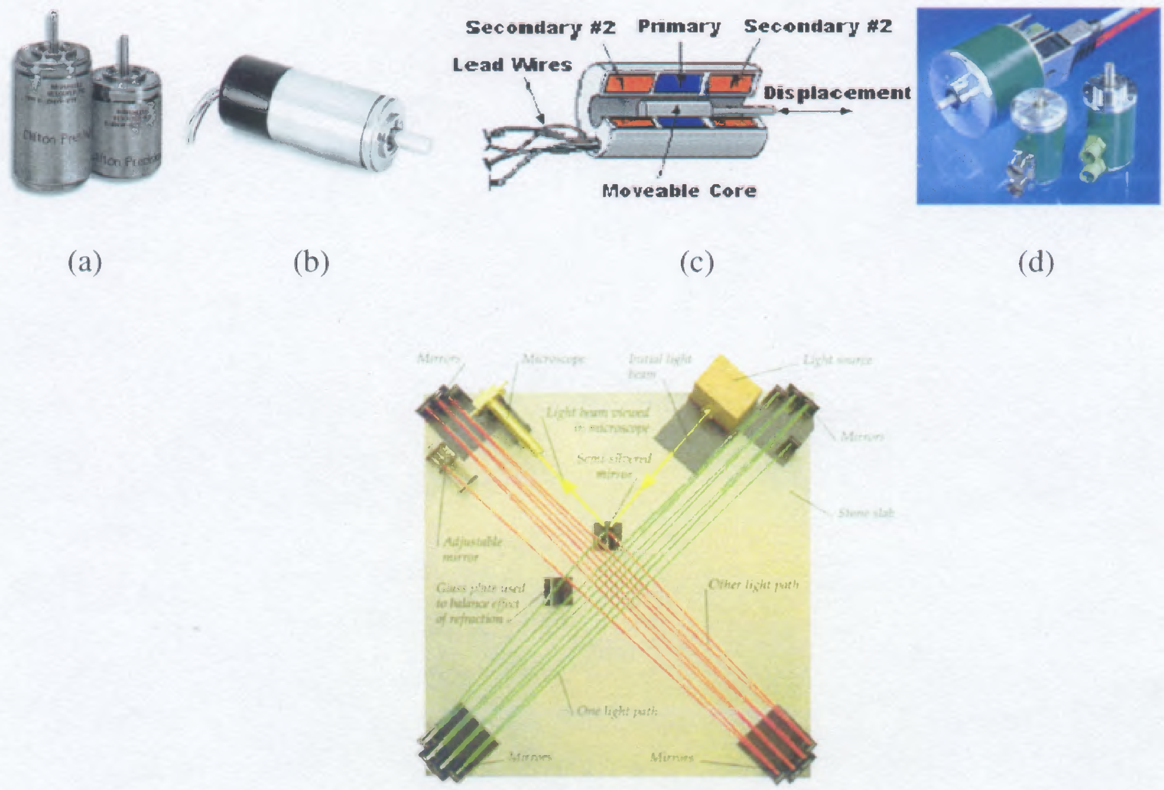


Figure 2.2 Servomotors.

Feedback system

The function of the feedback system is to assure that the table and workpart have been properly located with respect to the tool. It could be triggered by analog sensors such as synchros, revolvers, and linear inductive scales, or digital sensors such as binary encoders, rotary pulsers, linear optical scales, and laser interferometers. Figure 2.3 shows some example sensors.



(e)

Figure 2.3 (a) Resolver, (b) Synchros, (c) Inductive linear scales, (d) Binary encoders, and (e) Laser interferometer.

Ballscrews

A ballscrew shown in Figure 2.4 and 2.5 is a mechanical device that replaces the sliding friction of leadscrews with the rolling friction of ball bearings placed between the screw and nut members. A ballscrew performs at very high mechanical efficiency and with much less energy consumption for a given load. As compared to conventional screw drives, predictable wear life and smooth quiet operation are also obtained [8].

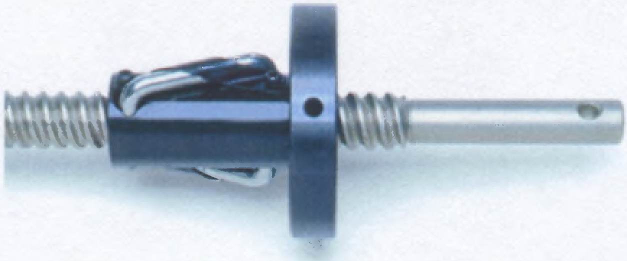
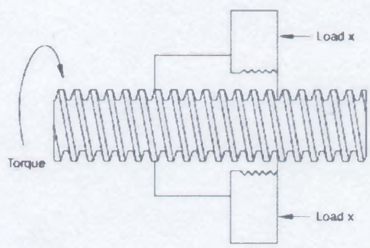


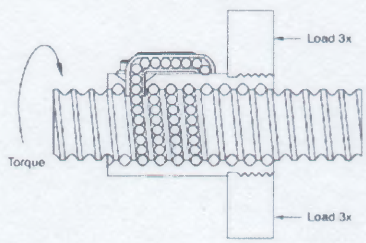
Figure 2.4 Ballscrew.

Mounting Ballnuts

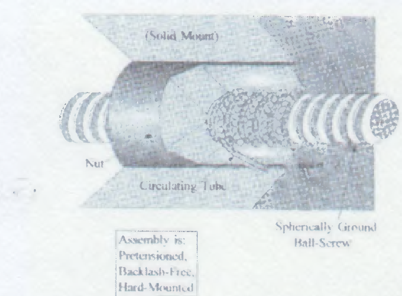
Ballnuts are typically mounted in mating flanges as shown in Figure 2.5, A to restrain the nut from rotation and translation and are sufficient when loads are axial. If significant side loads are present, support rails should be used in parallel with the ballscrew. The longer and the smaller the ballscrew diameter, the greater the possibility of column loading limitations.[8]



(a)



(b)



(c)

Figure 2.5 Mounting Ballnuts and Ballscrews; (a) conventional screw, (b,c) Ballscrew.

The servomotor is hard mounted on the end of a ground screw that is coupled with a recirculating ballnut assembly, which allows zero screw backlashes.

- **Tools.** All parameters associated with the tool such as diameter, length, rpm, and other geometry features should be saved in CNC control memory. The controller of CNC machine should have the capability to chose the right tool for that dedicated program. Tools examples are shown in Figures 2.6 and 2 .7.

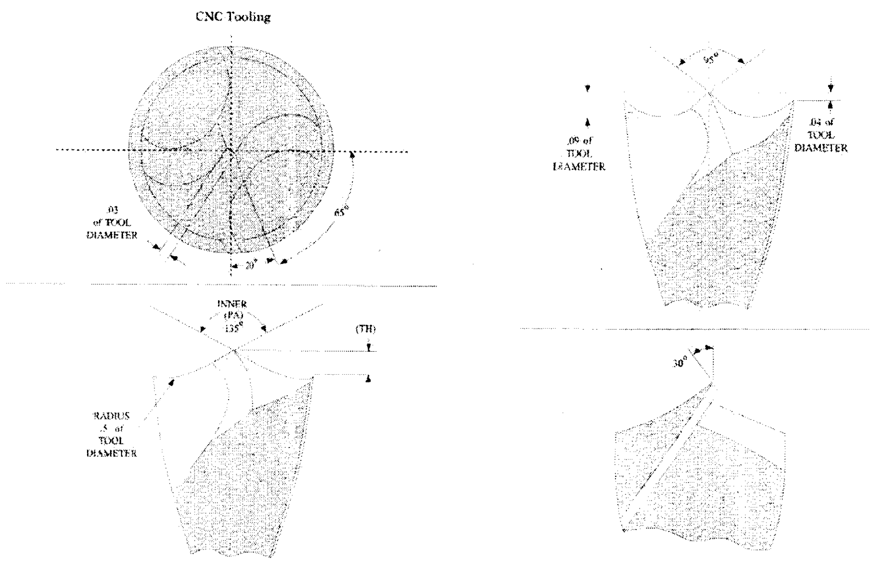
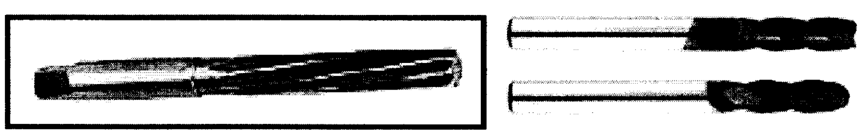


Figure 2.6 Geometrical properties for the tool.



(a) (b)

Figure 2.7 Tools, which are used in (a) NASA II milling machine, (b) drilling operation.

2.2.2 Control System

- The control system consists of the following major parts; machine control unit (MCU), data processing unit (DPU), and control loop unit (CLU). MCU consists of a microcomputer and other related control hardware that store the program of instructions and execute them by converting each command into mechanical action of the processing equipment (e.g. machine tools), one command of a time. Figure 2.8 shows an MCU structure

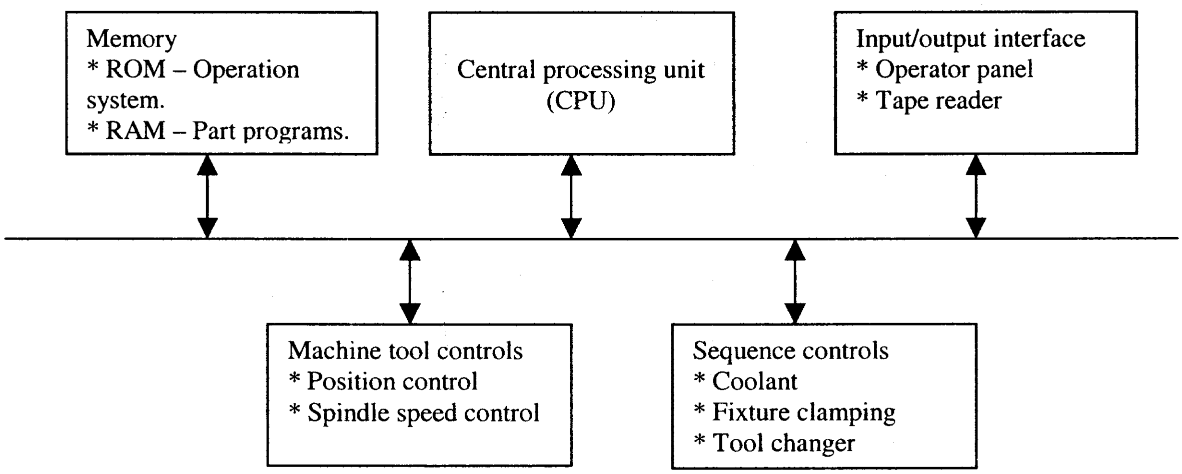


Figure 2.8 Configuration of CNC machine control unit

The main functions of the DPU are to read the part program, decode the part program statement, process the decoded information, and pass the information to the control loop unit (CLU). In addition, it positions each axis of the machine tool, and directs the motion of the axis, the feed rate and cutting speed.

The functions of the CLU are to receive data from the DPU, convert the data to control signals, operate the drive mechanisms of the machine, receive feedback signals about the actual position and velocity of the axes, and instruct the DPU to read new instructions from the part program when the operation has been completed. Figure 2.9 illustrates a schematic diagram of a CNC machine.

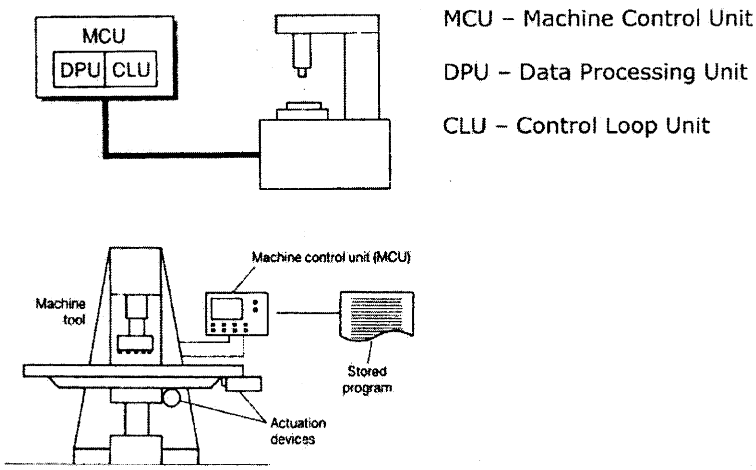


Figure 2.9 Schematic diagram that shows the MCU, DPU, and CLU used in a CNC machine.

2.2.3 Coordinate System

The most basic important programming concept of numerical control is to provide the mean of locating the tool in relation to the workpiece. Figure 2.11 below shows three major programming axes, X,Y, and Z, However, there are three more axes; a, b, and c, representing the motion around each axis X, Y, and Z respectively.

The axes maybe referenced on the bases of two major systems; fixed zero system (absolute zero) and float zero system. The fixed zero system is a numerical control system in which all-positional dimensions, both input and feedback are given with reference to a common datum point. Float zero system is a characteristic of a machine control unit that allows the zero reference point to be established at any point along an axis.[9]

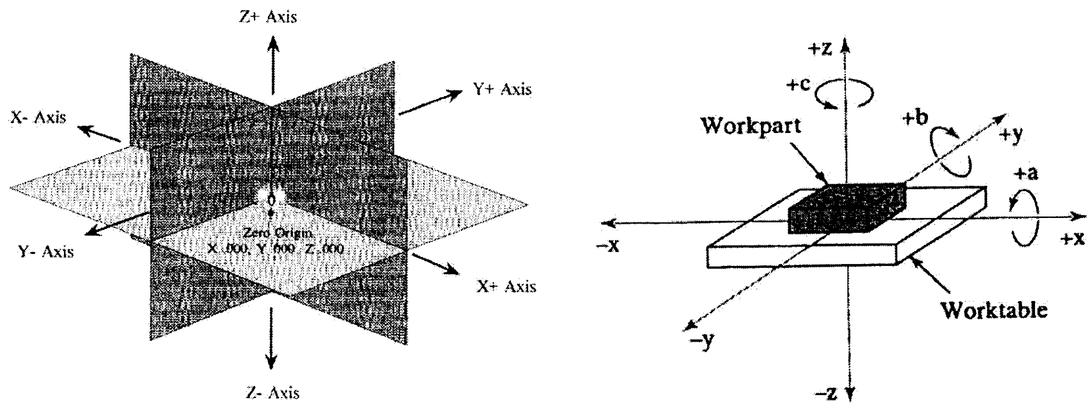


Figure 2.10 Visualization for coordinate system.

2.2.4 Motion Control System

The motion control system can utilize the following three control motions:

- Point to point control
- Straight cut control
- Contouring control

Point to point control (PTP)

The objective of PTP is to move the cutting tool to a predefined location. The motion maybe programmed as a sequence of movements along the X and Y-axes or direct movement between two points by simultaneously controlling the X and Y-axes drives. Drilling, tapping, boring riveting, and sheet metal bunching are examples of this kind of control motions. [27] See Figure 2.12.

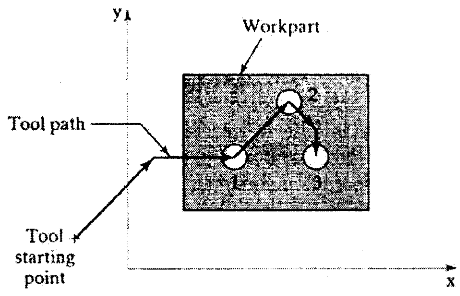


Figure 2.11 Point to point control system.

Straight Cut control

Straight cut control provides a limited degree of control during the positioning of the tool from one point to another. That can be parallel to one of the major axes or it can be performed at 45°. Figure 2.13 shows the straight cut operation.[27]

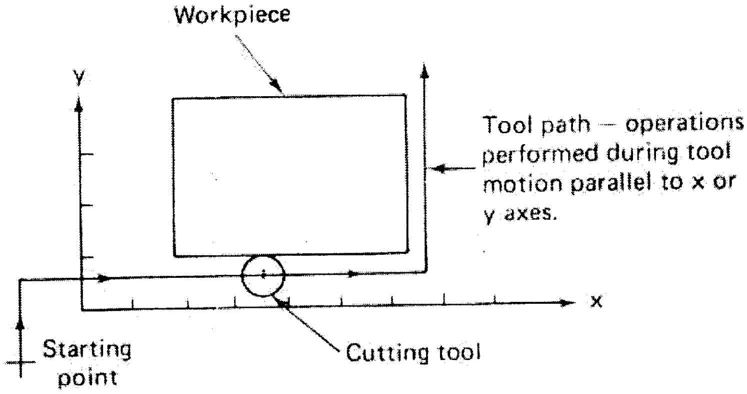


Figure 2.12 Straight cut control system.

Contouring control

Contouring control is recognized for its ability to control continuously the cutting tool path in all directions. An example for contouring control is shown in Figure 2.14.

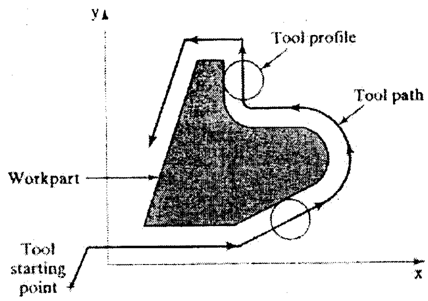


Figure 2.13 Contouring control.

2.2.5 Number of Axes

In machine tools, the cutter may typically move in multiple directions with respect to the workpiece or vice versa. Therefore the controller may drive more than one machine axis. In table 2.1, a classification of machines is presented on the basis of their number of, axes and Figure 2.15 shows some machines with their number and direction of axes.

Table 2.1 Classification for the Number of Axes of CNC Machines

Number of Axis	Description
Two axes machines	Generally in two orthogonal directions in a plane (e.g. lathe, punch presses, flame and plasma arc, cloth cutting machines, electronic component insertion. And some drilling machines) Machine tool controller is able to control the tool along only two axes simultaneously.
Two and one half axes machines	The machine movements are in planes parallel to the x.y plane. Moves in the Z.direction are drilling or for in feed or cutter retraction.
Three – axes machines	The movements are generally along the three principal directions (x, y, and z) , (e.g. milling, boring, drilling, and coordinate measuring machine). The tool can be moved along any curve by simultaneous control of the three axes, but the tool orientation does not change with tool motion.
Four axes machines	Typically the movements are three linear and one rotary axis (e.g. lathe fitted with supplementary milling heads).
Five axes machines	Normally involve three (x, y, and z) axes, with rotation about two of these – normally x and y, and are generally milling machines.

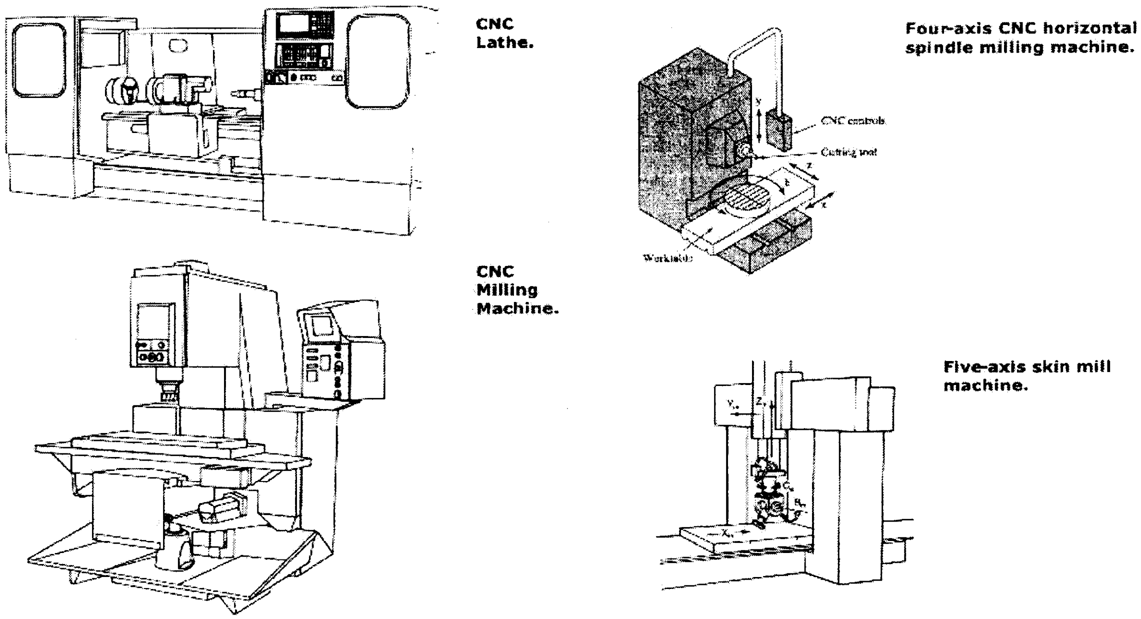


Figure 2.14 Classifications of the CNC machines according to their axes.

2.2.6 Control Loop System

The control loop system can be classified as open and closed loop system. The significant feature of the open loop system is that there is no feedback system; as shown in Figure 2.16. The information flows from the input media to the processor and storage memory through signal forms, the latter sends them to the motor controller, which drives the motor according to those signals.

A closed loop system is able to control precisely the position of the worktable through a feedback system. Figure 2.17 shows a closed loop system, which has the same operation as open loop system, except the there is an additional rout for signal. When the motor finishes the motion there a module is triggered which consists of a feedback device and comparing unit, to compare what was sent with what was achieved and direct the necessary correction.

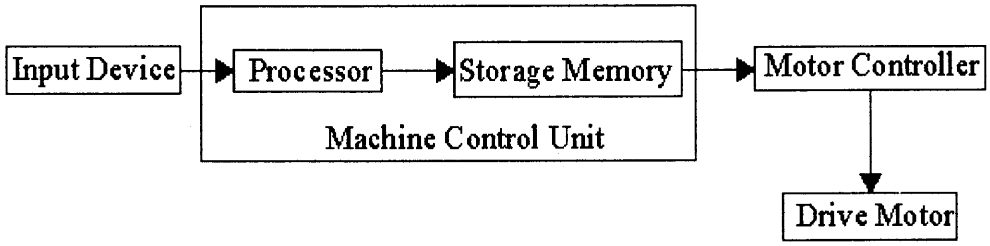


Figure 2.15 Open loop control system.

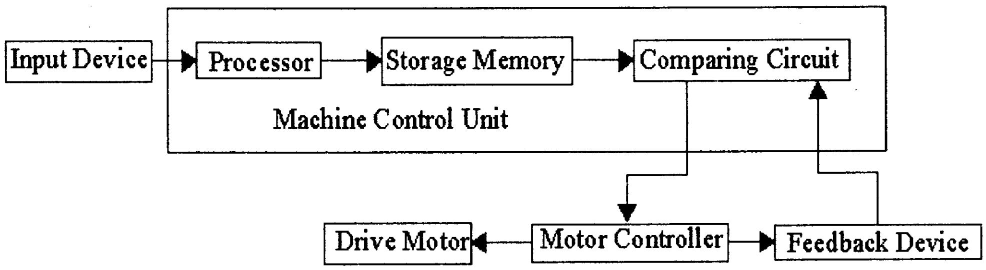


Figure 2.16 Closed loop control system.

2.3 Numerical Control/Computer Numerical Control/ Direct Numerical Control

An NC machine uses a tape reader to deliver the part program to the MCU. The MCU has storage capacity and can process only one command at a time.

2.3.1 Digital Computer for NC

Digital computers in NC can be done through Incorporating

1. Direct numerical control.
2. Distributed numerical control

2.3.2 Direct Numerical Control (DNC)

Direct Numerical Control is exercised when computer is used to control several machines simultaneously. This type of control was implemented first in the late 1960s. Instead of using a punched tape reader to enter the part program into the MCU, the program was transmitted to the MCU directly from the computer, one block of instructions at a time. This mode of operation was referred as BTR.(behind the tape reader).

Direct numerical control consists of four components classified as central computer, bulk memory at the central computer site, set of controlled machines, and telecommunication lines to connect the machines to the central computer. These components are shown in the Figure 2.18.

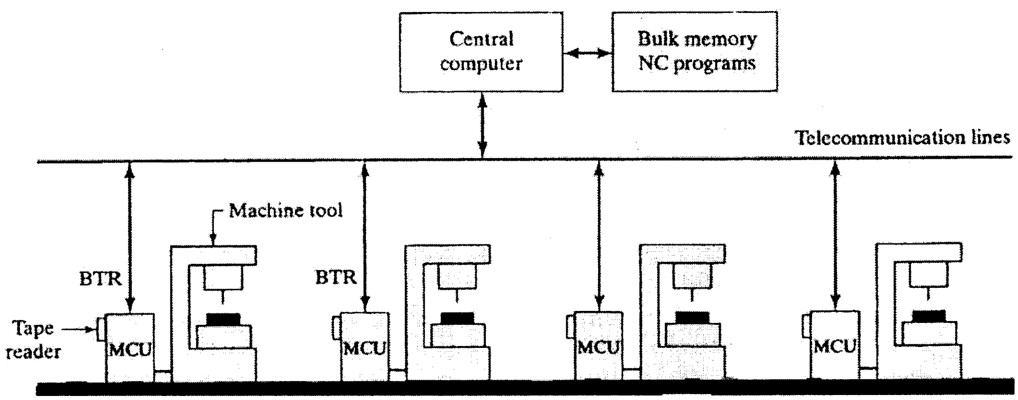


Figure 2.17 General configuration of a DNC systems. Connection to MCU is behind the tape reader.

Advantages of a DNC

- ✓ High reliability of central computer compared with individual hard-wired MCUs
- ✓ Elimination of the tape and tape reader.
- ✓ Control of multiple machines by one computer.
- ✓ Improve computation capability of circular interpolation.

✓ Part program stored magnetically in bulk memory in a central location.

Disadvantages

✓ High investment.

✓ There is problem when the central computer goes down.

2.3.3 Distributed Numerical Control (DNC/CNC)

As the number of CNC machine installations grew during the 1970s and 1980s, DNC emerged once again, but in the form of distributed computer system, or distributed numerical control (DNC). For both DNC and DNC/CNC systems, the machine operation data can be reported to central computers for the provision of workshop management information, and for the incorporation of the machine tool and other manufacturing equipment into a large integrated system.

There are several ways to configure a DNC/CNC system as shown in Figures 2.19 a & b. Figure 2.19arepresents switching network configuration and Figure 2.19b represents local area network LAN.

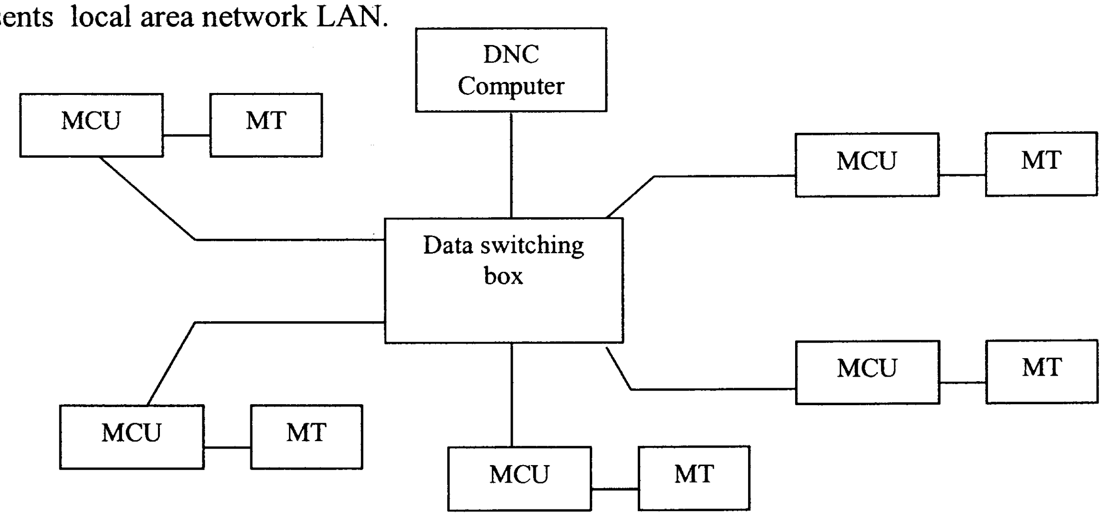
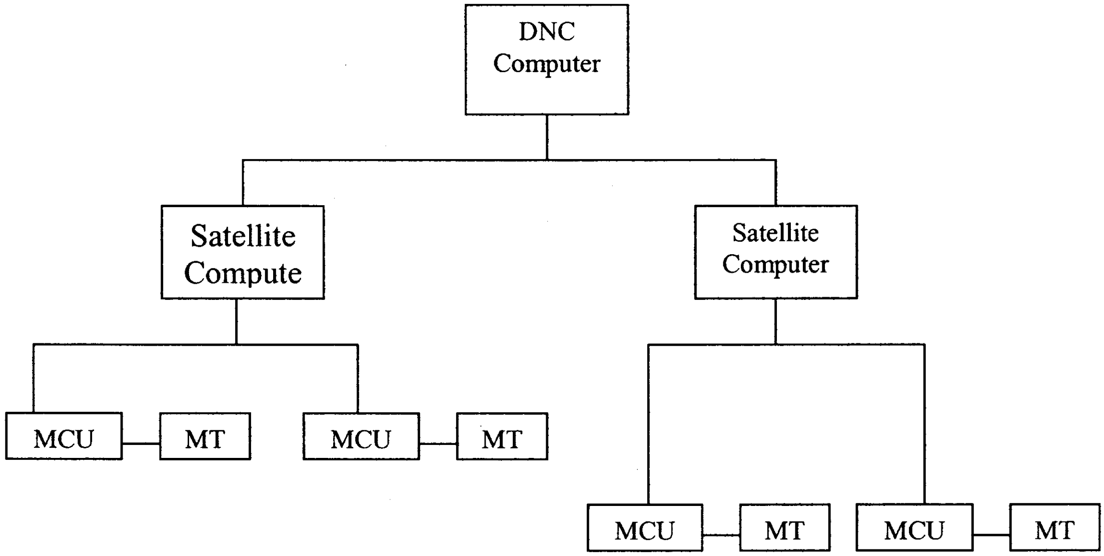


Figure 2.18a Configuration of DNC: switching network.



(b)

MT: Machine Tool

Figure 2.18b Configuration of DNC: LAN.

2.4 NC Part Programming

The following four part-programming methods are used to program NC machines

1) Manual data input – MDI
2) Manual part programming
3) Computer – assisted part programming
4) Part programming using CAD/CAM.

The four method are shown schematically in Figure 2.20.

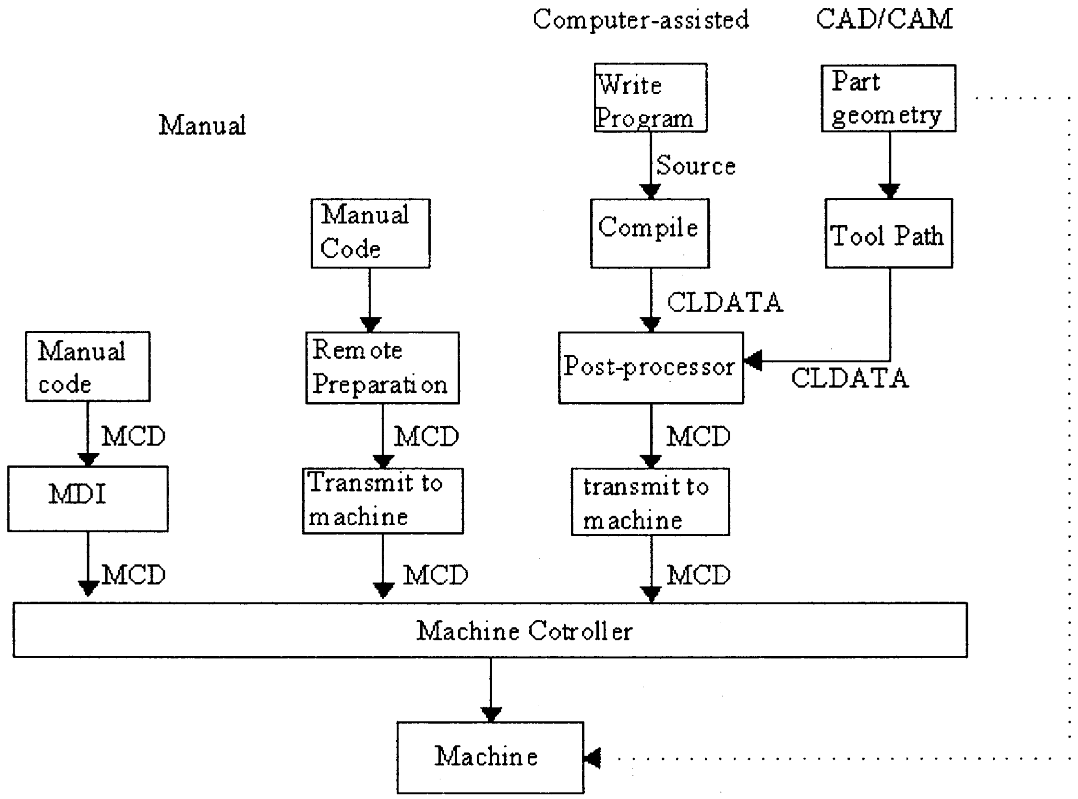


Figure 2.19 Schematic diagram for part programming methods.

2.4.1 Manual Data Input – MDI

Under manual data input the operator manually enters the part geometry data and motion commands directly into the MCU prior to running the job. MDI is useful in small machine shops. It introduces NC to small machine shop without the need to acquire special NC part programming equipment.

2.4.2 Manual Part Programming

Under manual part programming the programmer prepares NC code using a low – level machine language. The program can be written by hand and coded as punched tape or other storage media, or entered directly onto a computer equipped with NC part programming software, which writes the program onto the storage media. Manual part programming is mostly suited for point-to-point (drilling and spindle contouring jobs milling and turning when only two axes are involved).

2.4.3 Computer-Assisted Part Programming

In computer-assisted part programming, the machine instructions are written in English, like statements that are subsequently translated by the computer into low-level machine code that can be interpreted and executed by the machine tool controller. As shown in Figure 2.2, widely used languages are Automatically Programmed Tools (APT) and COMPACT II.

The main tasks of the programmer are to defining the geometry of the work part and to specifying the tool path and operation sequence.

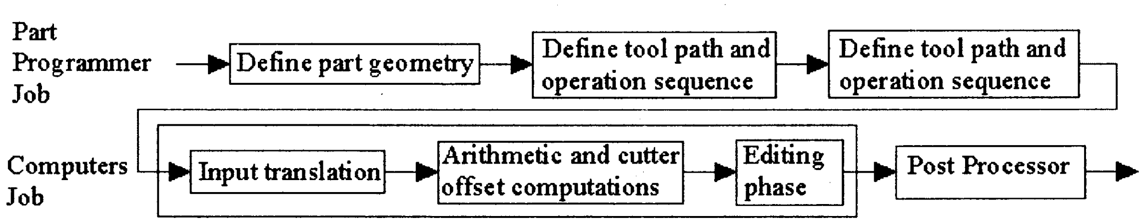


Figure 2.20 Tasks in computer assisted programming.

2.4.4 NC Part Programming Using CAD/CAM

In this programming, the part program is directly prepared from the CAD part geometry, either by using NC programming commands included in the CAD/CAM system or passing the CAD geometry into a dedicated CAM program.

CAD/CAM systems provide facilities to display the programmed motion of the cutter with respect to the workpiece, which allows visual verification of the program and the ability to edit interactively a tool path with the addition of tool moves, standard cycles, and perhaps APT macros (or the equivalent from other languages).

2.5 Data Preparation for Numerical Control

A post-processor is used to convert the machine-independent code format into a format suitable for the machine tool (machine control data, MCD). The machine receives instructions as a sequence of blocks containing commands to set machine operations, parameters, dimensional, and speed data. The classification of identifiers for the commands is as follows:

1- N. Sequence number: Is simply the identifying number for the block, in ascending numerical order, but not necessary in a continuous sequence.

2- G. Preparatory functions: Prepare the MCU for a given operation, typically involving a cutter motion.

3- X, Y, Z, A, or B Dimensional Data: Contain the location and axis orientation data for a cutter move.

4- F – Feed functions: Are used to specify the cutter federates to be applied.

5- S – Speed functions: Are used to specify the spindle speed, or to setup parameters for constant surface speed operation.

6- T – Tool functions: Are used to specify the cutter to be used, where there are multiple choices, and also specify the particular cutter offset.

7- M – Miscellaneous functions: Are used to designate a particular mode of operation, typically to switch a machine function (such as coolant supply or spindle) on or off.

2.6 Case Study for NJIT FMS

Chamfering program

Chamfering operation takes place by chamfering 7" X 7" Plexiglas block in 45° as shown in Figure 2.22. Olivetti machining center through CNC instructions shown in table 2.2 does chamfering operation.

Table 2.2 Suggested Program for Olivetti Machining Center " Chamfering Operation"

Sequence number	Preparatory functions	X	Y	Z	S	M	Notes
N001	G54	0.000	0.000				Rapid travel to start point
N002				.0.500	...	03	Adjust Z height and start cutting
N003		.7.00					Start cutting and move in negative X direction
N004			.7.00				Continue cut and move in negative Y direction
N005		+7.00					Continue cut and move in Positive X direction
N006			+7.00				Continue cut and move in negative Y direction
N007		+3.00					Move away from Piece
N008	G54	0.000	0.000	0.000			Rapid travel back to start
N009						05	Turn off motor
Program End							

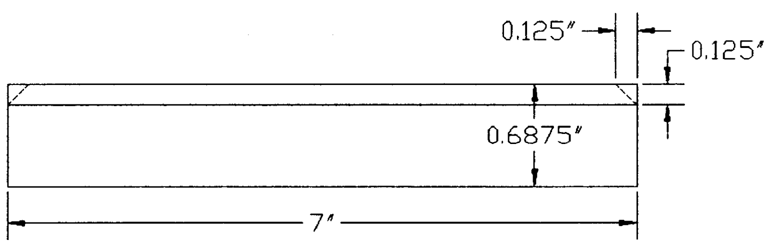


Figure 2.22 Dimensions of the chamfered block.

Drilling and milling program

Drilling and milling operations performed as drilling four holes, a hole in each corner. The milling operation performs fabricating NJIT FMS on the top surface of the work piece. Appendix C has the CNC program instructions to perform both operations. In milling operation or any similar operation, there are special motions for the cutting tool path; such as circular motions, these special motions have been formulated in mathematical formulas to facilitate their CNC programming. Examples for useful formulas are shown in Appendix B.

CHAPTER 3

INDUSTRIAL ROBOTS AND INTERFACE WITH CAD SYSTEM

3.1 Introduction

Robotics is a wide field currently sought after for research and development. There are many robot software available today. New software are released periodically, they become increasingly user-friendlier, compatible with working the environment, and possess more powerful features to control the robot. However, these software are designed to control one specific robot or a unique family of robots. Recently, software have been developed that are compatible with the robots of any manufacturer. The price of the package is affected by the complexity of its programming. For example, there are packages that cost $25000 or more, like the PLACE graphic simulator.

The software used one in this chapter is Workspace™ 3 and works in the DOS environment. There are new versions of this software, such as Workspace™ 5, which works in Windows.

Workspace™3 is an off-line programming, graphical robot simulator that offers accuracy and compatibility regardless of what major manufacturers robot is used. The benefit of Workspace™3 is that it helps to visualize of the robot process quickly before it goes into the production stage.

3.2 Programming Techniques

Robots are programmed using manual setups leadthrough programming, computer like robot programming languages, and off-line programming. Manual setup techniques are usually associated with limited sequence robots where limit switches and mechanical stops provide robot control.

Leadthrough programming involves teaching a particular task by moving the robot's manipulator through a sequence of motions and recording the position coordinates. Computer like robot languages involve a specific set of instructions that provide robot control, from a simulated CAD model, Off-line programming is accomplished by sending a set of instructions to the robot controller. This minimizes the time a robot must be taken out of production in order to accomplish the programming.

A PC based CAD system interfaced with an industrial robot is beneficial over the standard robot programming techniques since robot programs can be generated automatically by a set of graphical instructions displayed on the computer screen. Once proper kinematics and geometries are established, a graphical simulation of the workcell's function will occur in real-time, allowing for modification and improvement before generated programs are downloaded into the robot's controller.

3.3 Robot Software

A robotic McDonald Douglas CAD software system consists of four modules, namely PLACE, BUILD, COMMAND, and ADJUST. The relationship among these modules is shown in Figure 3.1.

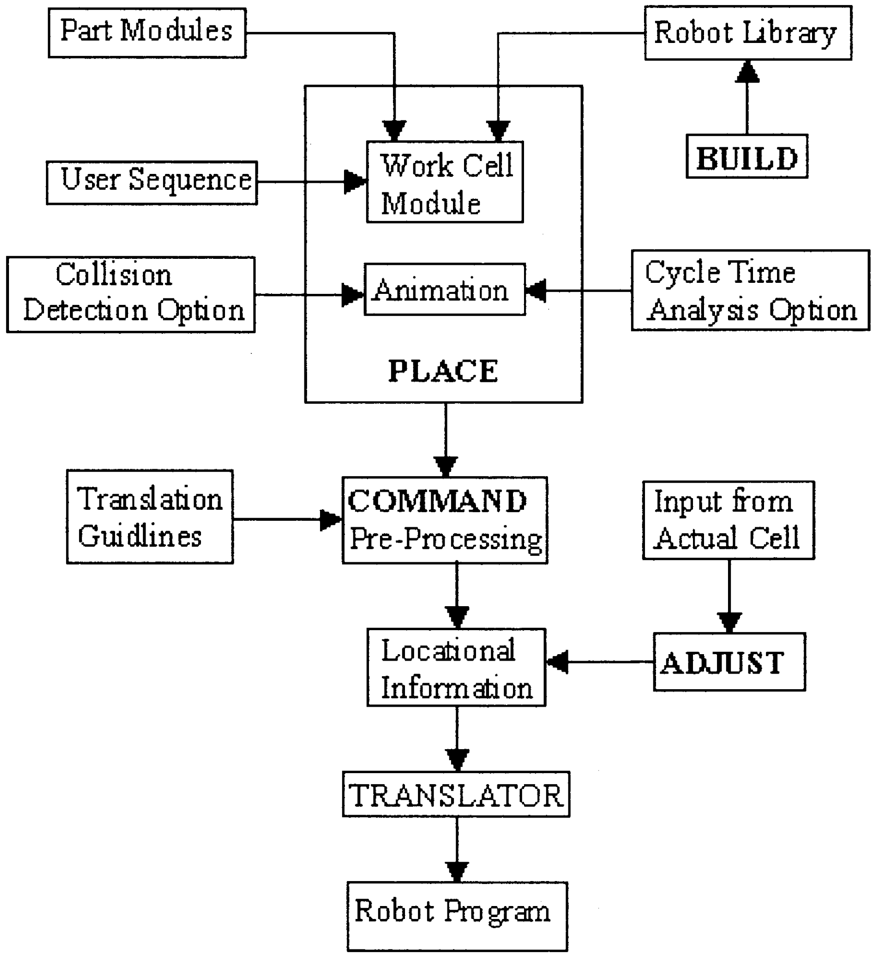


Figure 3.1 Process flow from simulation to translation.

The PLACE (Positioner Layout And Cell Evaluator) module is used to develop a model of the workcell similar to the actual working system. It is also useful in simulating all the operations of the FMS cell on the system so that the various layouts and motion sequences can be animated and evaluated.

The BUILD module enables the user to graphically build any additional robots or other devices that are not in the CAD data base. These geometric models of the new robots and devices can be automatically combined with their unique kinematics description for future animation in PLACE.

The COMMAND module is used for programming the robots off-line. COMMAND is used in conjunction with PLACE and a specific robot program translator to generate a complete robot program that can be downloaded to and executed on the robot controller. A powerful feature of COMMAND permits the user to associate groups of logic instructions with specific robot positions defined by a place sequence.

The ADJUST module is used in conjunction with a probe attached to the robot end effector. It is designed to modify the locations of the robot end effector in a PLACE workcell so that the physical dimensions of the robot match the actual locations of the corresponding end effector in the actual FMS cell. This is a fast and efficient way of resolving any discrepancies that may exist between the physical dimensions of the actual robot and the dimensions of the simulated model and also between the actual cell and its computer model.

3.4 Robot Anatomy

All robots have joints and links. The anatomy of robot is a description of its joints and links.

IBM 7535 Robot

The IBM 7535 robot was shown in Figure 1.9 has special end effectors to perform drilling operation. The robot has SCARA configuration. The arm is very rigid in the vertical direction allowing the robot to perform drilling operation by moving the drill only up and down in vertical direction. This robot consists of number joint and links. It has five degrees of freedom with three types of joints; orthogonal, rotational, and revolving. In orthogonal joint. The relative movement between the input link and the output link is a linear sliding motion. The input and the output links are perpendicular to each other. It is called **O** joint and is shown in Figure 3.2a. Rotational joint provides a rotational relative motion of the joints with the axis of rotation perpendicular to the axis of the input and output links. It is called **R** joint and is shown in Figure 3.2b. In revolving joint. The axis of the input link is parallel to the axis of rotation of the joint, and the axis of the output link is perpendicular to the axis of rotation. It is called **V** join, and shown in Figure 3.2c.

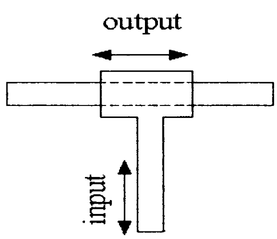


Figure 3.2a Orthogonal joint.

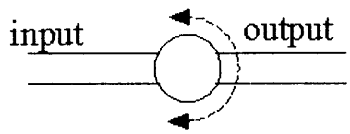


Figure 3.2b Rotational joint.

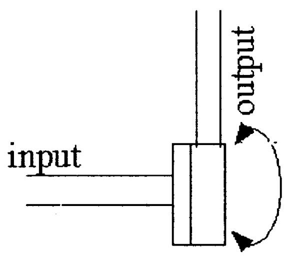


Figure 3.2c Revolving joint.

GE P-50 Robot

The GE P-50 robot was shown in Figure 1.10 has a vacuum gripper to enable picking up/ depositing a block from/to the cart. It has a jointed arm configuration, with the arm being able to swivel about the base. This robot consists of rotational joints and twisting joints. The rotational joint allows for a rotational motion of the links with the axis of rotation perpendicular to the axis of the input and output links. It is called **R** joint, and is shown in Figure 3.3a. The twisting joint permits a rotary motion, but the axis of rotation is parallel to the axis of the two links. It is called **T** joint and is shown in Figure 3.3b.

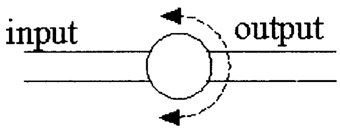


Figure 3.3a Rotational joint.

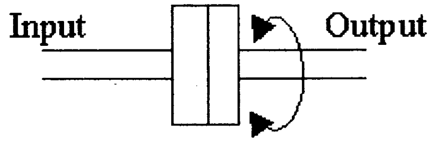


Figure 3.3b Twisting joint.

GMF M1 Robot

GMF M1 robot was shown in Figure 1.11 has a mechanical gripper, and a cylindrical configuration, It consists of a vertical column, relative to which an arm assembly can be moved up and down. This robot consists of an orthogonal joint, twisting joint, and linear joint. The orthogonal and twisting joints were discussed earlier. In linear joint the relative movement between the input link and the output link is a linear sliding motion, with the axes of the two links being parallel. it is called **L** joint. And shown in Figure 3.4.

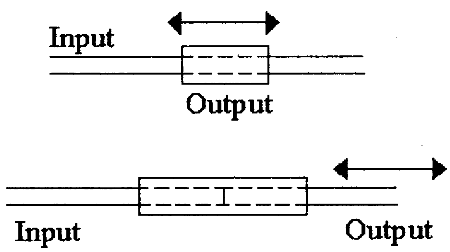


Figure 3.4 Linear joint

3.5 WorkSpace™3 Robot CAD System

With the assistance of modern computer technology, design, simulation, control, planning, management, or any area of manufacturing is no longer difficult to model. It has been said that "3D simulation has revolutionized the way that engineers can work".[6]. The following sections describe how the computer simulation done by Workspace™ 3 was used to simulate the drilling operation done by the IBM 7535 robot.

Workspace™3 is widely used in industry tool to design, model and simulate. It can be used in off-line programming, which means that it can prepare the program and download it to the robot without interrupting production. The features, specifications and applications of Workspace™3 are discussed below.

3.5.1 Features

Workspace™3 is a 3D graphical simulation software system for robotics and mechanisms. It is a productive tool designed to make the implementation of advanced manufacturing systems as simple and economical as possible. Workspace™ increases productivity and reduces time [34]. The features are:

1. Quickly model work cell layout
2. Demonstrate process and plant design
3. Prepare real time animation for presentation
4. 3D CAD system constructive solid geometry

3.5.2 Specifications

1. Teach point files
2. Graphical representation results
1. Ability to easily off-line programming
2. Kinematics modeler

3.5.3 Applications

1. Arc and spot-welding
2. Materials handling
3. Paint spray
4. Palletizing
3. Electronics assembly

Table 3.1 is an example of controlling the robot motion using Workspace™3. It describes the joints and points positions for the SCARA industrial robot for a drilling operation. Initially after the robot is built, the joints have home position values in the X, Y and Z axes as: X: 708", Y: 2", and Z: 204", and the values of rotational axes a, b, and c around each axis are a:0° b:0° and c:0°, if the joint is taught to move the point 1 then the coordinates will be changed and the new points called TP1, its values are shown in the table below. So there are four teach points to perform drilling operation done by the IBM 7535 robot

Table 3.1 Coordinates of the Points with Joints Motions of IBM 7535Robot

Points Joints	HOME	TP1	TP2	TP3	TP4
1	0	0	0	0	0
2	0	45	45	45	45
3	0	0	45	45	45
4	0	0	0	75	0
X	708	618	618	618	618
Y	2	223	221	221	221
Z	204	204	204	129	204
a	0	0	0	0	0
b	0	0	0	0	0
c	0	0	90	90	90

3.6 Case Study: Sample Program for Drilling Operation done by NJIT FMS

The program presented here shows how WorkSpace™3 can be used to program the IBM 7535. It also shows the parameters, which should be considered in the programming. To understand this program, the following definitions are needed:

- Karel 2. The language for the simulation and for writing this program.
- Teachpoint (TP). The point, where the joint should rest by the end of the movement.
- Position. The defined position for each teachpoint.
- NullObject. Hidden object used to join two objects.
- AttachObject. A command likes the same but to attach the block to the cart.

Referring to the Figure 3.5. If the yellow bar rotates about the X-axis by Φ degrees, the transformation matrix for that rotation is Rot (X, Φ). Similarly, if the rotation takes a place around Y-axis or Z-axis, the rotation matrices are Rot (Y, Φ) and Rot (Z, Φ) respectively. These matrices are shown below.

$$Rot(X,\Phi)=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & \cos\Phi & -\sin\Phi & 0\\ 0 & \sin\Phi & \cos\Phi & 0\\ 0 & 0 & 0 & 1\end{bmatrix} \qquad Rot(Y,\Phi)=\begin{bmatrix}\cos\Phi & 0 & -\sin\Phi & 0\\ 0 & 1 & 0 & 0\\ \sin\Phi & 0 & \cos\Phi & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$Rot(Z,\Phi)=\begin{bmatrix}\cos\Phi & -\sin\Phi & 0 & 0\\ -\sin\Phi & \cos\Phi & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 0 & 1\end{bmatrix}$$

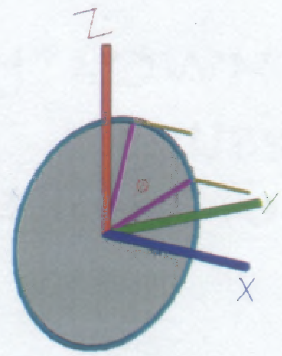


Figure 3.5 Rotational axes around X-axis by angle Φ

The program below traces the robot from an ISOMETRIC view. It consists of three types of statements; auxiliary statements, geometry statements, and motion statements.

The first five statements in the program are the auxiliary statements. The program begins with the declaration of the program name, which is DRILING. Then it declares the language (Karel2), the memory is 1024kb, the name of the robot IBM 7535, and then it moves to teachpoint declaration, {then there are four teaching points and their positions are defined early in the table 3.1, these teachpoints are classified as geometry statements}. For the last category of statements (motion statements). There are many commands illustrated as the following, the workpiece moves to a determined position. Then the robot arm comes above this position (TP2), moves the drill down (TP3), rotates the drill (TP4), and then the robot arm moves to home and repeats the cycle again and again. The motions of the conveyors and the robot are completely controlled by PLC.

```
PROGRAM DRILLING
. LANGUAGE KAREL 2
. MEMORY 1024
. ROBOT IBM7535
. TEACHPOINT DECLARATION
VAR
        TP1: POSITION
        TP2: POSITION
        TP3: POSITION
        TP4: POSITION
BEGIN
%INCLUDE 2#
. MOVE OBJ 'NULLOBJECT1', 201.31,709.62, .208.31,250
        MOVE TO TP2
        MOVE TO TP3
        MOVE TO TP4
        MOVE TO $ HOME
END DRILLING
```

Figures 3.6 and 3.7 show examples of robots used in NJIT FMS drawn by the well known CAD package AutoCAD. These files can be exported and imported by

Workspace ™3. The whole FMS cell can be displayed by CAD as shown in Appendix A, which shows many drawings for NJIT FMS.

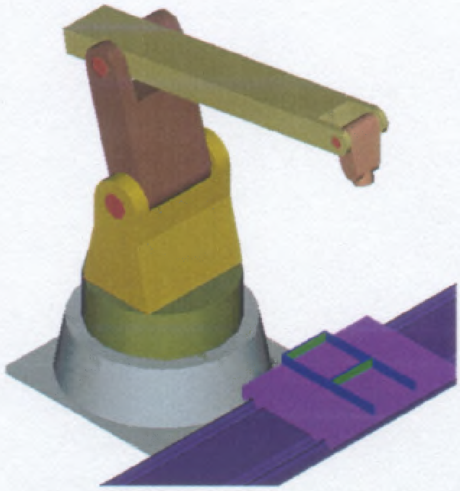


Figure 3.6 CAD modeling for GE P-50 robot.

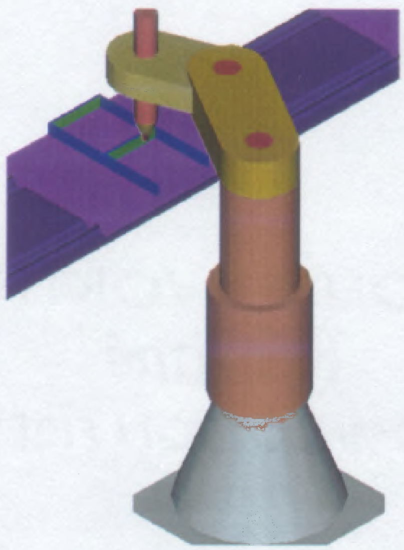


Figure 3.7 CAD modeling for IBM 7535 robot.

CHAPTER 4

COMPUTER VISION INSPECTION

4.1 Introduction

Over the past twenty years, computer vision has been used in wide array of manufacturing applications, including robotics, electronics and semi conductor manufacturing. These were among the first to embrace the technology and currently account for about half of the computer vision applications found on factory floors.

However acceptance is rapidly growing throughout the entire manufacturing sector, with computer vision systems now in place in food processing, pharmaceuticals, wood and paper, plastics, metal fabrication and other industries. Until recently, the limiting factor in vision-based robotic control has been the ability to perceive and react in complex and unpredictable surroundings.

Computer Vision and Image Understanding is a prestigious journal devoted to the dissemination of research in areas relevant to computer vision. Papers are published on all aspects of image analysis, from low-level processing, as in early vision, to high-level symbolic processing needed for recognition and interpretation. More specifically, the following topics are particularly central to what is published in the journal:

- Computational models of the human visual system
- Early vision
- Data structures and representations needed for high-level vision
- Shape representation and extraction

- Range data analysis
- Use of motion for recognition and interpretation
- Matching and recognition
- Architectures and languages for image processing
- Vision systems

4.2 Operations of Computer Vision

Computer vision inspection can be defined as a method of using a computer to analyze an image obtained from a video camera. The operation of the vision system can be divided into the following three functions:[27]

1- Image acquisition and digitization

2- Image processing and analysis

3- Interpretation

These functions and their relations are illustrated schematically in Figure 4.1.

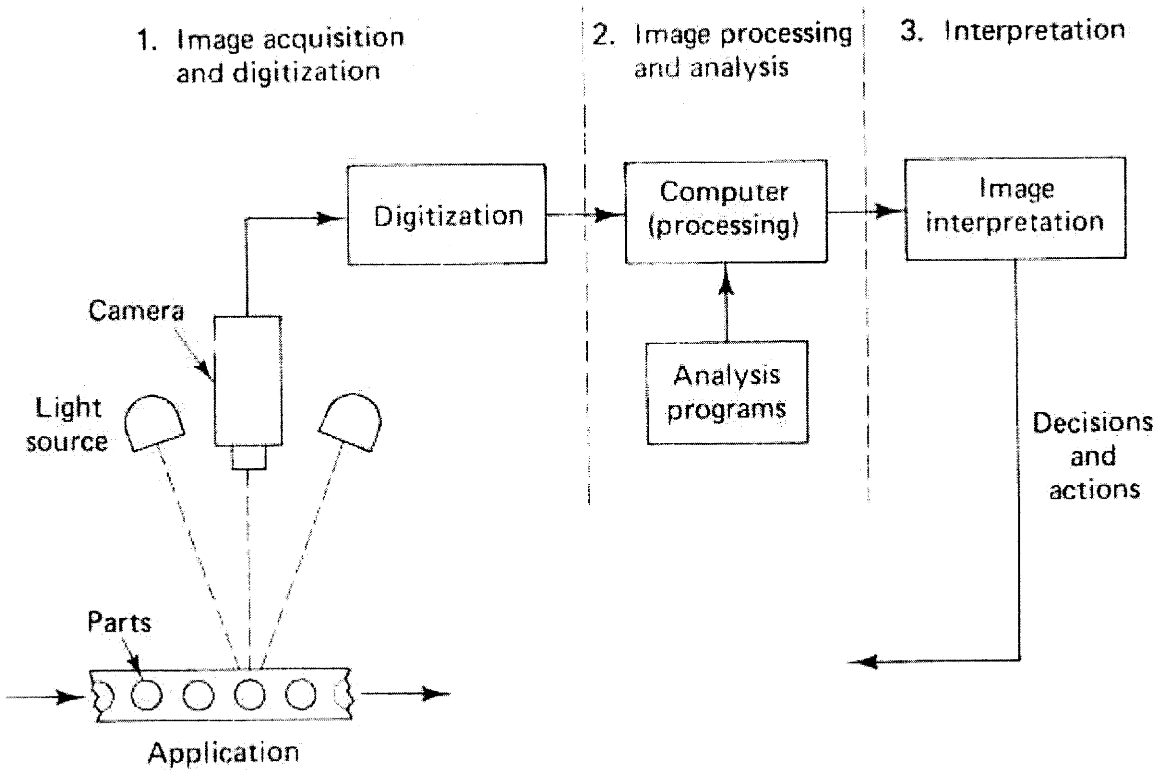


Figure 4.1 Basic functions of a machine vision system.

4.2.1 Image Acquisition and Digitization

Image acquisition and digitization is accomplished using a video camera and digitizing system to store the image data for subsequent analysis. The camera is focused on the workpart and an image is obtained by dividing the viewing area into a matrix of discrete picture elements (Pixels), in which each element has a value that is proportional to the light intensity of that portion of the scene. The intensity value for each pixel is converted into its equivalent digital value. The operation of viewing a scene consisting of a simple object is depicted in Figure 4.2.

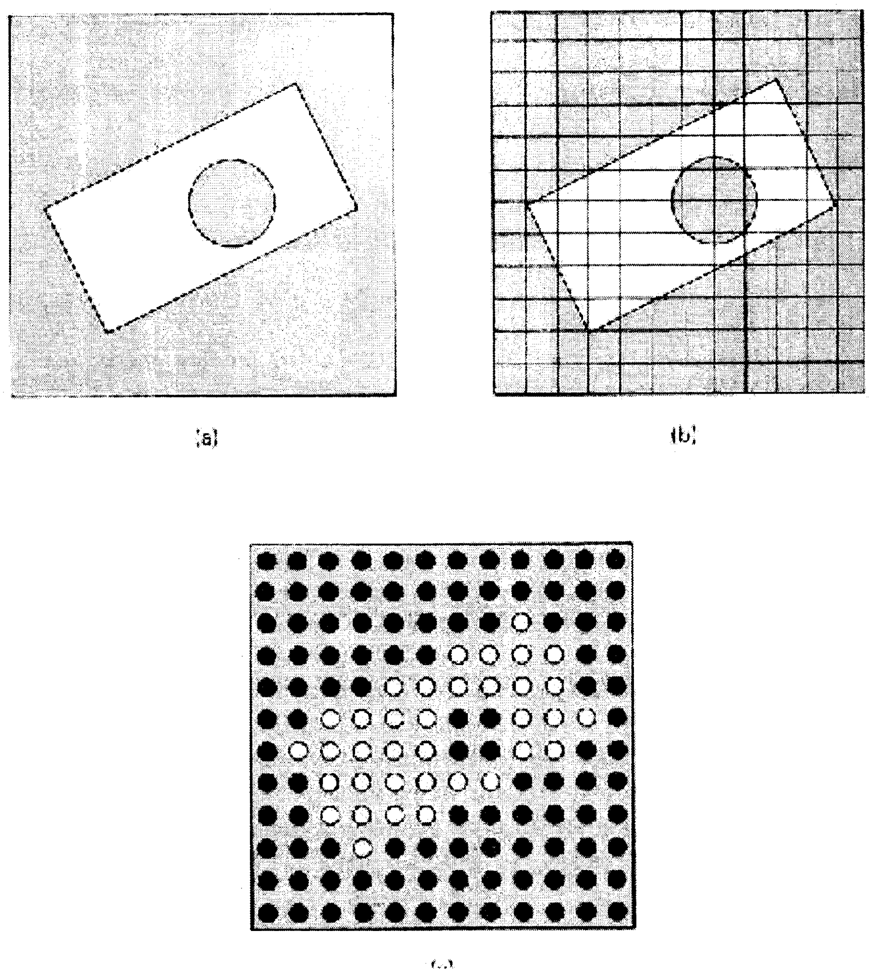


Figure 4.2 Dividing the image into a matrix of picture elements, where each element has a light intensity value corresponding to that portion of the image.

4.2.2 Image Processing and Analysis

The amount of data, that must be processed and analyzed, is significant. The data for each frame must be analyzed within the time required to complete one scan (1/30 sec). A number of techniques have been developed for analyzing the image data in a vision system. The segmentation technique is used to define and separate regions of interest within the image. Feature extraction methods are used to determine the features (e.g. length, width, or diameter) based on the object's area and its boundaries.

There are two commonly used segmentation techniques. The threshold technique, which involves the conversion of each pixel intensity level into a binary value. This is done by comparing the intensity value of each pixel with a defined threshold value. If the pixel value is greater than the threshold, it is given the binary value of white (e.g. 1). If the value is less than the defined threshold, it is given the bit value of black (e.g.0).

Another segmentation technique is edge detection. It determines the location of boundaries between an object and its surroundings in an image. This is accomplished by identifying the contrast in light intensity that exists between adjacent pixels at the borders of the object.

4.2.3 Interpretation

The interpretation function is usually concerned with recognizing the object, a task termed object recognition or pattern recognition. The objective of this task is to identify the object in the image by comparing it to predefined models or standard values. Two commonly used techniques are template matching and feature weighting. The most basic template matching technique is one in which the image is compared, pixel-by-pixel, with a corresponding computer model. Within certain statistical tolerance, the computer determines whether or not the image matches the template. Several examples of this are shown in Figure 4.3.

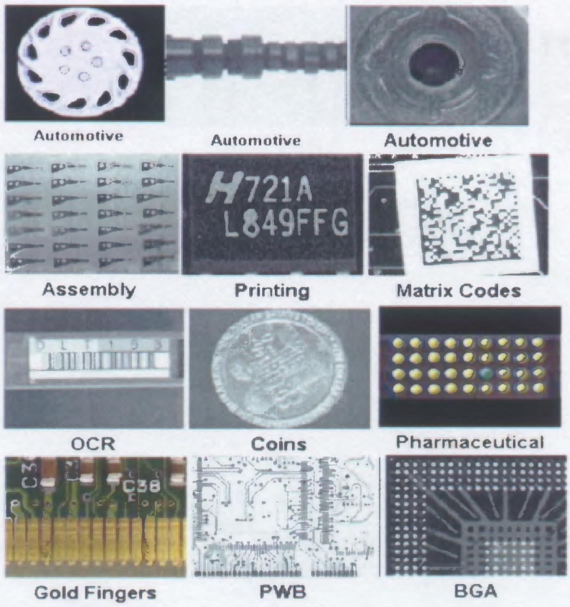


Figure 4.3 Diverse applications for which machine vision has been implemented.

The process begins with an image that is formed from a camera lens using a camera receiver. The receiver is a CCD (charged coupled device) array, which converts the image into a grid of separate points, called pixels. The pixels are seen as squares on the grid. Each pixel is light sensitive and therefore has an electronic charge, which is representative of the amount of light, the lens projects onto them.

The electronic signals are sent to a processor where an analog to digital converter coverts the signals into a series of binary numbers and stores them into memory. Each pixel is therefore assigned a numerical value that represents a particular intensity of light. The light intensity number corresponds to a grayscale indicator that uses values from 0 to 63 (0 begin black and 63 begin white).

Intelligent Visual Sensor (IVS) systems can analyze the converted image in a number of ways. IVS use algorithms that can identify measurements, edge detection, part defects, and other parameters. These algorithms can be used simultaneously to detect acceptable and rejectable parts. During an inspection, the system could use a triggering device, such as a photoelectric sensor, to enable the camera to acquire an image of the object that is being inspected. The image would then be converted to a digital array and stored into a buffer. The vision system could apply an algorithm such as counting edge pixels and comparing them to a standard value for this measurement. The values generated can be used to calculate other functions within the IVS system before sending an output through RS232 communications to an external device such as a programmable logic controller.

4.3 The Itran IVS Computer Vision System

The IVS system used for the project is a feature sensor system. The feature sensor contains area tools, which can be configured in different ways. There are quite a few components of the system, which need to be configured for the application. The software used to configure and edit the system is the SensorEdit software supplied by Itran. The software is used on a PC, which contains a link card and cable used to communicate with the IVS.[14]

The pixel resolution for Itran IVS system is 320 x 240 pixels. The IVS system has sub-pixel resolution capabilities to 1/32 of a pixel. This is done by using mathematical operations of differentiation and interpolation on the surrounding pixel values. Because of this technology, the accuracy of the system is greatly increased.

The total processing time of the IVS system is constant of each inspected part at 67 msec. Time is needed for scanning (at fixed rate) and the implementation of a parallel processing technique. The system is actually processing four images at one time. There are four steps for each inspection, and each of the four images that are being processed advance to the next step. The four steps are as follows:

1) Read inputs, acquire image, apply locator and lightmeter.

1) Apply the vision algorithms.

2) Process the worksheet calculations.

3) Process outputs.

4.3.1 Obtaining an Image

The first step in obtaining an image is to place a part in the inspection area and within the field of view. Using the software, the system is configured for continuous inspection in order to obtain a live video image on a display monitor. Lighting and focus adjustments are made until the image is optimized. Next, using the Itran software, a converted digital image of the object is obtained. A magnifier tool, which enables one to see the values of the pixels within the image, can be used to determine if any additional lighting or focusing issues need to be addressed to obtain a clear contrasted image. The magnifier also helps determine the threshold settings that need to be used for the inspection.

4.3.2 Area Tools

The area tool is a technique used to measure certain selected functions within a selected (or highlighted) area within the field of view. The functions include sum edge energy, count edge pixels, sum gray values, and count threshold pixels. For this application, the count threshold pixels function was used which provides the total number of pixels values above or below a specified threshold value within the area tool. The threshold value must also be determined. The IVS software provides a histogram of the pixel values within the area tool, which is used as a guide in determining the optimum threshold value. The count threshold function was set to count the number of pixels that had a value above the threshold value of 9.

The area tool was inserted and placed over the image of the largest part in order for it to be large enough for all six different parts. After the application was downloaded to the IVS, each part was manually placed in the inspection area to measure the area tool value for that part. Once all the values were obtained, the output of the system was configured. This procedure is used after uploading an image (a new image from the camera), and positioned the locator tool; these tools are listed as following:

1. Select Edit Arc Tools.
2. Select a Brush Shape.
3. "Paint" an Area Tool.
4. Select Inspection Method.
5. Repeat For Additional Tools.
4. Resolve Tool Conflicts.
5. Program the I/O.
6. Program the Math Worksheet.
7. Download and Test the Application.

4.3.3 Screen Messages, RS232 Outputs and Discrete I/O

The IVS system allows one to create outputs in three different forms: discrete I/O, screen messages, and RS232. The output can be configured using Boolean logic or can be set to true or false. The discrete I/O is opto isolated hardwired outputs, which can be wired to any external device. The screen massages are displayed on the vision system display monitor. The RS232 output information can be sent to a wide variety of RS232 terminals including PC's and PLC's.

Screen messages and discrete I/O are created using Boolean logical formulas. A sample formula could be: IF (AREA1>24000 AND AREA 1<26000,TRUE, FALSE). Here 24000 is the least number of threshold pixels and 26000 is the maximum number of threshold pixels. The AREA1 is the name of the area tool, TRUE is the 'then' statement and the FALSE is the 'else' statement. The message display is then configured to determine what was to be displayed. Each part is then assigned an output port, which is used as hardware interface to the PLC.

RS232 outputs are configured exactly the same way as the screen messages and discrete I/O. The only difference is that the RS232 outputs setup needs to be configured in order to send the data in the proper format for the receiving device. Items such as baud rate, data bits, stop bits, and terminators are configured.

4.4 The FS11 – Feature Sensor

The FS11 is an innovative, low cost, non-contact, feature sensor. It is capable of high-speed operation, performing multiple feature inspections per part. As shown in Figure 4.5.

Figure 4.4 FS11-feature sensor.

The FS11 is primarily used following automatic assembly, machining or forming operations. Among the numerous uses for the FS11 are verifying:

- That holes have been drilled in sheet metal parts
- The absence of flash on a modeled part
- A subassembly has been properly added to the operation
- A package is properly formed
- A bottle cap is present and correctly shaped

The FS11 delivers image derived process information to production control devices such as programmable logic controllers, personal computers, or any control system. It can be directly connected to process machinery using standard industrial I/O.

On-line operation

The FS11 grabs from a video camera a 2D image of the part to be inspected. The image is processed in 16.7 milliseconds using Iran's proven and sophisticated gray scale technology. Up to 128 feature inspections can be made on each image.

A powerful comprehensive set of math operations combines and manipulates the inspection results, allowing that implement real time solutions. It can be used to perform inspection and other tasks associated with manufacturing processes. A built-in shift register tracks parts and permits effective reject control, even on high-speed processes (up to 60 parts/sec).

Simplified System Integration

The FS11 has been designed to simplify its integration into a manufacturing line. Its features include:

- Built-in material handling shift register for effective rejection control, even on high-speed processes
- Integrated sensor and strobe circuitry (for those systems requiring strobes)
- Built-in user menu for system setup, including options to control monitor display and camera setup

Benefits/Features

- Fast
  - All measurements made in 16.7 msec
  - Pipelined processing allows rates up to 60 parts per second
- Non-contact
  - 2D visual analysis of parts

- Easy to Use
  - Graphic setup environment on MS Windows 95 or more
  - Speed and response rate are unaffected by the complexity of inspection
  - Automatic compensation for object motion and lighting variation
- Communications
  - RS 232
  - Discrete I/O
  - Built-in shift register for interfacing with material handling system
- Flexible
  - Measurements can be made along any line or contour
- Visual feed back provided for operators
  - RGB/monochrome RS170 monitor output
  - Real time display of images and vision tool graphics
  - Screen message reports results
- Meet special application needs
  - Sensor development kit allows tailoring the sensor to meet specific application demands

4.5 Inspection Method

In the SensorEdit program, there is a Method menu, which contains the methods used to control the computer vision system regarding the acceptance or rejection the inspected part. Several options are available on the this menu as indicated below:

1. Sum gray values. Sum the gray scale values of all pixels in the tool. Suppose there are four pixels in the tool having gray scale values of 20, 23, 24, and 26. This function returns a value of 93.

2. Count threshold pixels. Counts all pixels with gray scale intensity values equal to or above the threshold that has been set.

3. Count pixels below threshold. Counts all pixels with gray scale intensity values below the threshold that has been set.

4. Sum edge energy. Sums the edge strength values of all pixels in the tool.

5. Count edge pixels. Counts the pixels with edge strength values equal to or above the threshold.

The focus will be "Count threshold pixels", "Counts pixels below threshold" and "Count edge pixels". Changes can be done to the threshold values by selecting image brush thresholds Figure 4.5, a dialog box displays a histogram of the image, in this box, lower and upper thresholds can be updated to show the qualifying pixels.

The histogram is a vertical bar chart set on a horizontal axis of 63 gray-scale values. The height of each bar shows the relative number of pixels at each gray-scale. Value. For example, if the bar over the gray-scale value 33 is twice as high as the bar over the gray-scale value 32, then there are twice as many pixels in the region with gray-scale value of 33 as there are with a value of 32.

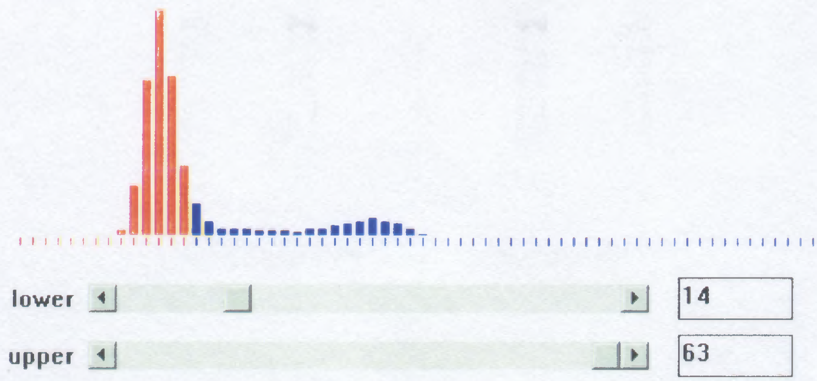


Figure 4.5 Tooth brush threshold.

4.6 Project Description

The IVS system was configured to identify "NJIT FMS", which is fabricated on the NASA II CNC milling machine and shown in Figure 4.6. The IVS system scans the part as it passed the lens and matches its image with qualifying logical expressions that were created for each part. Screen messages were displayed for the identification of each block accordingly.

Using the RS232 input of the IVS system, a terminal software program using windows software was used to display and store the inspection data for each "NJIT FMS" work part, make comparison with a predefined image and energize the robot to place each part the accepted or rejected bins

Figure 4.6 model of the inspected workpart.

CHAPTER 5

PROGRAMMABLE LOGIC CONTROLLERS

5.1 Introduction

Today manufacturing becomes increasingly flexible and fully automated to achieve faster and better quality production, and to stay on the competitive edge. Programmable logic controllers (PLCs) are used in most industrial applications control. They are considered as an integral and invaluable tool that helps designers and decision makers to better implement their long term manufacturing control plans by using computer hardware and software.

A PLC can be defined as a digitally operating electronic system designed for use in an industrial environment to implement specific functions such as sequencing, timing, counting and arithmetic control function and analog functions such as proportional-integral-derivative (PID). Ladder logic diagram LLD is used to program PLCs.

A Ladder Logic Diagram is a graphical programming language consists of a set of rungs each of which instructs the PLC to scan input(s) and activate output(s). A rung is bounded by two vertical lines representing the negative polarity on the left and positive polarity on the right. Each rung describes the current flow from component(s) on the left side of the rung (input(s)) to the right side component(s) of the rung (output(s)).

A PLC study is presented in this chapter. Components of PLCs in Section 5.2, functions and advantages of PLCs in Sections 5.3 and

5.4 respectively, and the basic logical gates of PLCs in Section 5.5. The case study for the PLC used in NJIT FMS is presented in Section 5.6.

5.2 PLC Devices

State-of-the art PLC devices are used as controllers in assembly lines, robots and other manufacturing facilities that facilitate precise control measurements. Those devices can be digital or analog and used as inputs to the system or outputs from the system. Examples of devices used with PLC are listed in table 5.1 and examples for the input devices used in NJIT FMS are shown in Figure 5.1

Table 5.1 Input and Output PLC Devices

Input Devices	Output Devices
Limit switch	Motor
Photo detector	Alarm buzzer
Pushbutton switch	Control relay
Control relay	Lights
Circuit breaker	Valves
Timer	Solenoid

(a) (b) (c)

Figure 5.1 Examples for input and out devices; (a) Limit Switch, (b) Photo detector, (c) Solenoid.

5.3 PLC Components

A PLC has the following components:

1. Input module
2. Output Module
3. Processor
4. Memory
5. Power Supply
6. Programmable Device

The components of a PLC controller and their functions are shown in Figure 5.2.

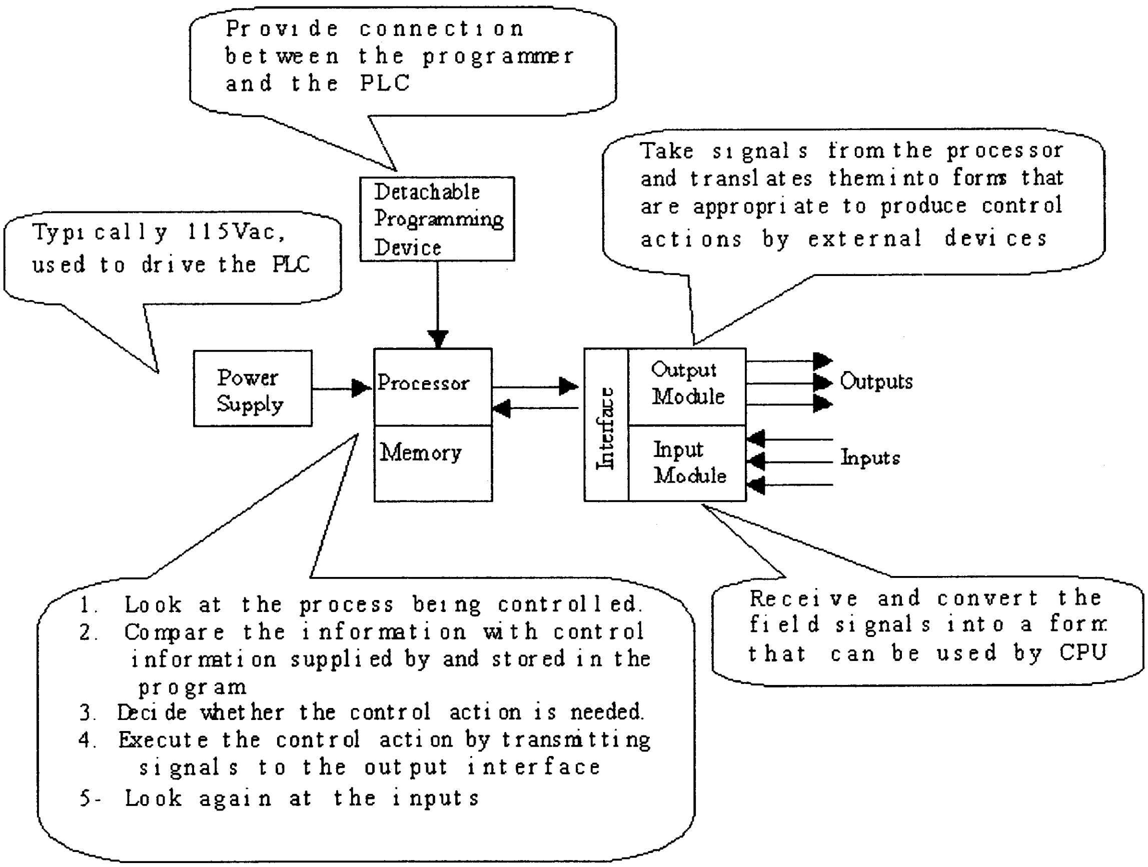


Figure 5.2 Schematic diagram of a PLC controller.

5.4 PLC Computer Functions

The functions that a PLC can perform are:

1. Control of each process station

2. Production control

3. Traffic control

4. Tool control

5.5 Advantages of PLC

PLC use offers the following advantages:

1. Increase system availability

2. Decrease downtime requirements to recover from failure

3. Decrease cost from material and man-hours for installation

4. Increase system feasibility.

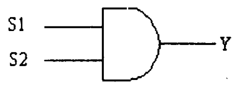
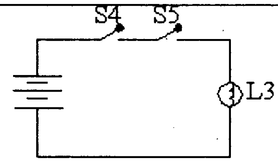
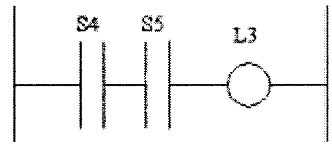
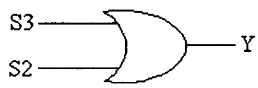
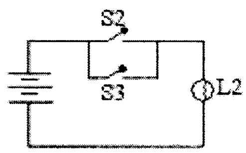
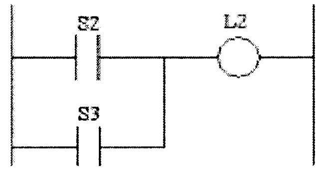
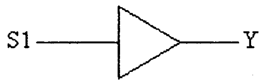
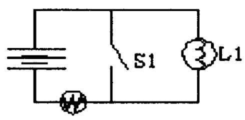
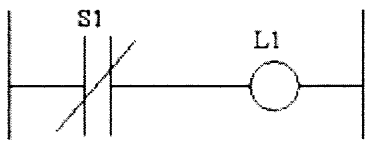
5. Increase flexibility to meet new requirements

5.6 Basic Logic Gates used in PLC (AND, OR, and NOT)

A logical AND gate outputs a value of 1, if all inputs are 1. A logical OR gate outputs a value of 0, if all inputs are 0. Logical NOT gate output is 1 if the input is 0, and vice versa.

Table 5.3 shows the three basic logic gates with their presentations as Logic gate, electrical circuits and LLD presentation.

Table 5.3 Basic Logic Gates Used in PLC

PLC Gate Name	Logic Presentation	Electrical circuit presentation	LLD presentation
AND		 S4 AND S5 =L3 S4 x S5 =L3	
OR		 S2 OR S3 = L2 S2 + S3 = L2	
Not		 $\bar{S1}$-L1	

For better visualization of how the programming language LLD is designed, see the example shown in Figure 5.4. In the first rung, pressing input switch I:1/1 activates the output O:6/1, which can be any output device. The next rung describes a logic AND gate. To energize output O: 6/2 both input switches or devices should be energized. The third rung describes a logic OR gate. Output O:6/6 can be activated if either one of inputs I:2/4 or I:6/12 or both should be pressed.

The following rung describes the latching concept in PLC programming. Once the switch I:2/4 is pressed or activated, the circuit is closed and output O:5/1 is energized. It will remain on, irrespective of whether the previous switch is off or on. The function of switch I:1/2 is to let the current flow through the circuit for the first time and to cut off the circuit whenever is needed, it might be used as emergency switch.

The fifth rung shows a timer element. When switch I: 2/2 is pressed the output goes on and the timer starts timing for four seconds. When the timing is over, output O: 6.12 goes off and the timer sends a signal to the following rung to activate output O: 6/4

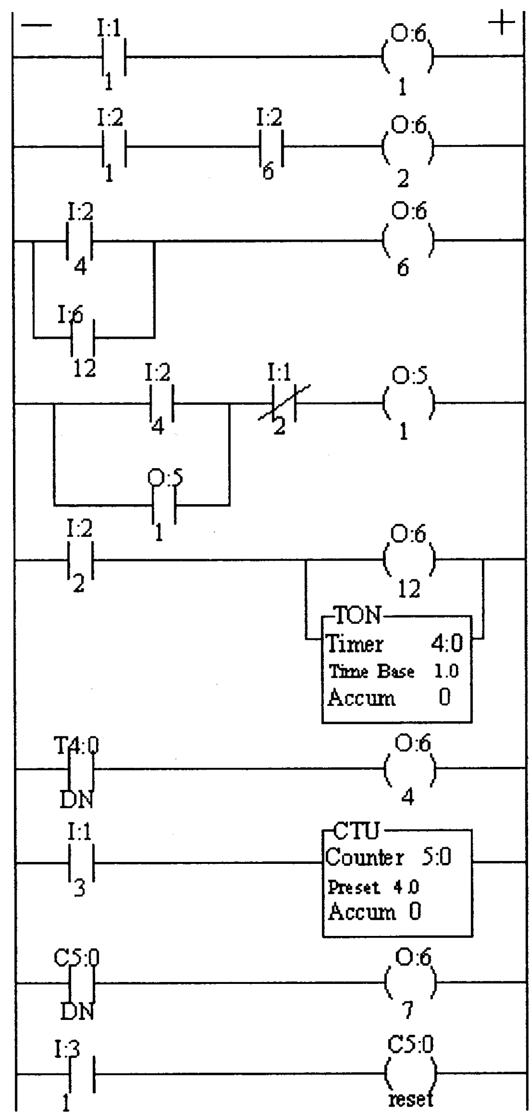


Figure 5.4 An example for LLD programming

The seventh rung shows counter element. Here after the switch I: 1/3 senses something 5 times, the counter sends a signal to the following rung to activate it and output O: 6/7 goes on. To reset the counter, a different input switch should be used. as shown in the last rung.

5.7 Case Study of NJIT FMS

Operational Descriptions

The working cycle for this FMS proceeds in the following five states:

State 1: Loading Carts State.

1. Initially all four carts on the conveyor system are empty and available for the raw materials to be loaded onto them from the parts presentation station.

2. The GE robot P-50 goes to the parts presentation station and loads four parts, one by one, onto the four carts on the conveyor system. The carts move clockwise as they are being loaded.

3. Once the four parts are loaded, the positions acquired by the four carts are shown in Figure 5.3

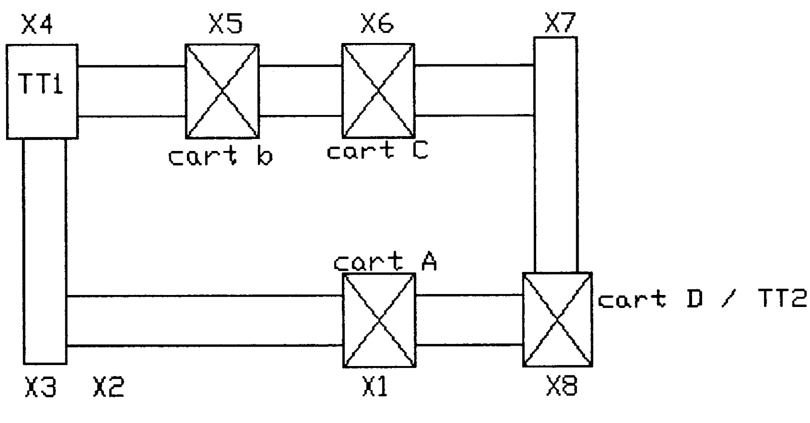


Figure 5.3 Loading state of the conveyor system.

State 2: Drilling Operation.

The IBM7535 robot drills four holes on each of the corners of each blank part as the cart stops at the drilling machine.

State 3: Chamfering Operation.

1. The GMF M1 robot moves to position x6 of cart C and picks up the part from the cart and places it into the fixture of the Olivetti machining center.

2. Once the part is loaded on the chamfering machine, the robot retracts, and the chamfering machine chamfers the edges of the upper surface as required.

3. After the chamfering machine operation, the robot moves to the Olivetti machining center to remove the part that was machined from the holding fixture back to cart C.

State 4: Milling Operation.

1. The GE P-50 robot moves to the conveyor to remove the part from the cart position X1 and loads it into the fixture located on the CNC machine table.

2. Once the part is loaded on the CNC milling machine, the robot retracts, and the milling machine mills the rectangular part as required.

3. After the milling machine operation, the robot moves to the milling machine to remove the part that was machined from the holding fixture.

4. The robot returns the finished part to the same cart on the conveyor.

State 5: Vision Inspection

1. A signal is sent to the vision camera to inspect the part.

2. The vision system analyzes the part and outputs a signal that directs the PLC to tell the robot to accept or reject the part.

3. The robot runs either an accept program to place the part in the accept bin or runs a reject program to place the part in the reject bin.

The entire operation with its control points is shown in Figure 5.5. For more information about the PLC – LLD used to control NJIT FMS cell refer to appendices E, F, and G

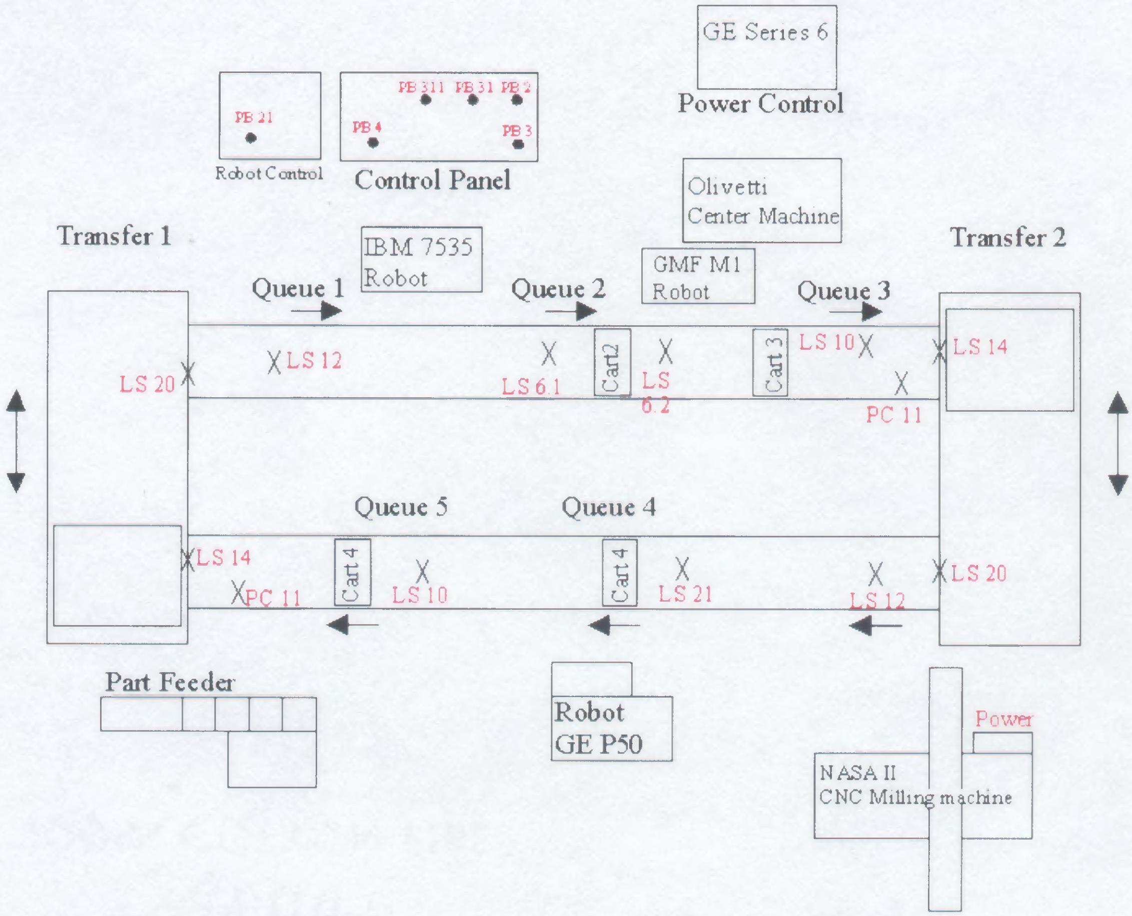


Figure 5.5 Control points of NJIT FMS operation.

CHAPTER 6

PETRI NET MODELING AND SIMULATION

6.1 Introduction

the use of technology and the application of control and management theories and techniques have revolutionized the flexibility of manufacturing. New control and modeling techniques are always sought for the purpose of achieving further improvements. A technique that has the potential for generating additional improvements is the use of Petri nets.

The focus of this chapter is primarily on Petri nets (PN) and their contribution to industry development. Definitions are discussed in section 6.2; classifications of PN in section 6.3; modeling methods in section 6.4; a case study of NJIT FMS in section 6.5; and finally the connection between Petri Nets and PLC in the last two sections.

6.2 Petri Net Definitions

Petri Net: A Petri net is a graphical and mathematical modeling tool, which is able to model concurrent, asynchronous, distributed, and parallel systems. The basic Petri net consists of four different components: Places, Transitions, Arcs, and Tokens.

Place: A Place is a basic Petri net component, which represents a condition and represented by a circle. If a place is a member of the input function of a transition, it is a precondition for that transition or event to occur. If a place is a member of the output function of a transition, it is a post-condition of that transition.

Transition: A transition is a basic Petri net component, which represents an event. The event may occur when all of the input places to the transition contain enough tokens to enable the input arcs to the transition. The occurrence of the event, also known as a firing of the transition, will result in tokens being deposited through each of the output arcs of the transition into the respective output places.

Arc: An arc is a Petri net component, which relates places to transitions and transitions to places, and has an associated weight, representing the number of tokens needed to enable the arc.

Token: A token is a basic Petri net component, which is thought of as residing in a 'place'. A token signifies that a particular place, or condition, is true. Multiple tokens residing in a place are usually representative of the existence of multiple resources.

Reachability Tree: A reachability tree represents all of the obtainable markings for a Petri net. The tree begins with the initial marking, with a line from the initial marking to a new marking for each enabled transition.

Marking: A mapping of tokens to places, which defines a state for the Petri net.

Live: A Petri net is live when there exist no terminal nodes in the net's reachability tree. For each marking in the reachability tree, there exists at least one transition that is enabled for that marking.

Safe: A place is said to be safe if, for all possible markings, the number of tokens in that place never exceeds one. The Petri net is declared safe if all of the places in the net are safe.

Bounded: A place is k-bounded when, for each marking in a reachability tree, the maximum number of tokens appearing in that place never exceeds k. A Petri net is j-bounded if all places in the net are bounded and j represents the maximum bound value of all places in the net. k represents maximum number of tokens in specific place.

Conservative: A Petri net is said to be strictly conservative if, for all possible markings, the total number of tokens in the Petri net always remains constant. A Petri net may also be conservative with respect to a weighting vector such that all markings when multiplied by the weighting vector are equal. [31&35]

6.3 Petri Nets

Petri net models can be either mathematical or applications

.

6.3.1 Mathematical Models

A Petri net is four-pillars:

PN= [P, T, I, O]

P: a finite set of places $\{P_1,P_2,\ldots,P_n\}$

T: a finite set of transitions, $\{t_1, t_2, \ldots, t_n\}$

I: an input function, (TxP) → {1,0}

O: an output function, (TxP) → {0,1}

M_o: an initial marking P→ N where N = {0,1,2,...}

< P, T, I, O, M_o> ......a marked Petri net.

To start analyzing the PN, assume the process shown in Figure 6.1.

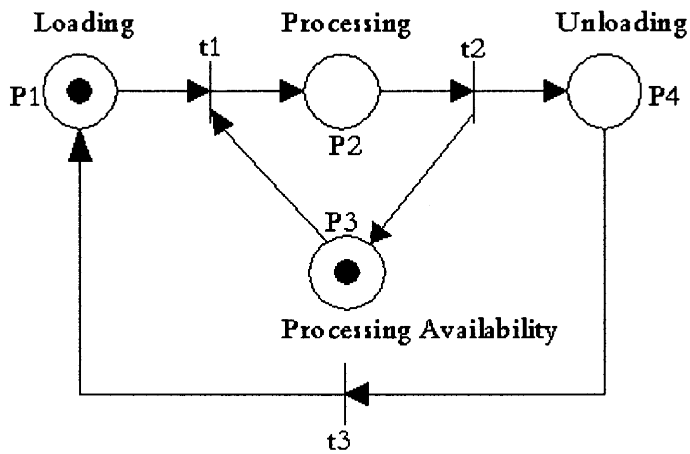


Figure 6.1 An example of processing which analyzes the mathematical modeling of a PN.

Where
P = {P1, P2, P3, P4}

T = {t1, t2, t3}

I =

	P1	P2	P3	P4
t1	1	0	1	0
t2	0	1	0	0
t3	0	0	0	1

O =

	P1	P2	P3	P4
t1	0	1	0	0
t2	0	0	1	1
t3	1	0	0	0

M_o = (1,0,1,0)

<u>Enabling Rule</u> A transition is enabled if every input place contains at least one token.

<u>Firing Rule</u> The firing of an enabled transition occurs by removing one token from each input place of the transition, and adding one token to each output place of the transition. The enabling and firing rules are illustrated in Figure 6.2

The above rules can be explained in detail using the Petri net example shown in Figure 6.1. It consists of four places and three transitions, initially $M_o = (1,0,1,0)$, so for t1 to be enabled it should have two tokens; one from P1 and another from P3. Both tokens are available in this example, so the firing takes a place and the token moves to P2, meaning that processing is activated. Transition t2 has one input and two outputs, so once the token is in P2, automatically t2 has been enabled, and the token moves to places P3, and P4. In this state t1 is not enabled because it doesn't have a token in P1 while t3 is enabled. So P4 fires the token to P1 and process recycles it self.. Figure 6.2 shows every enabled transition and their firing places. Table 6.1 describes the reachability tree for this Petri net

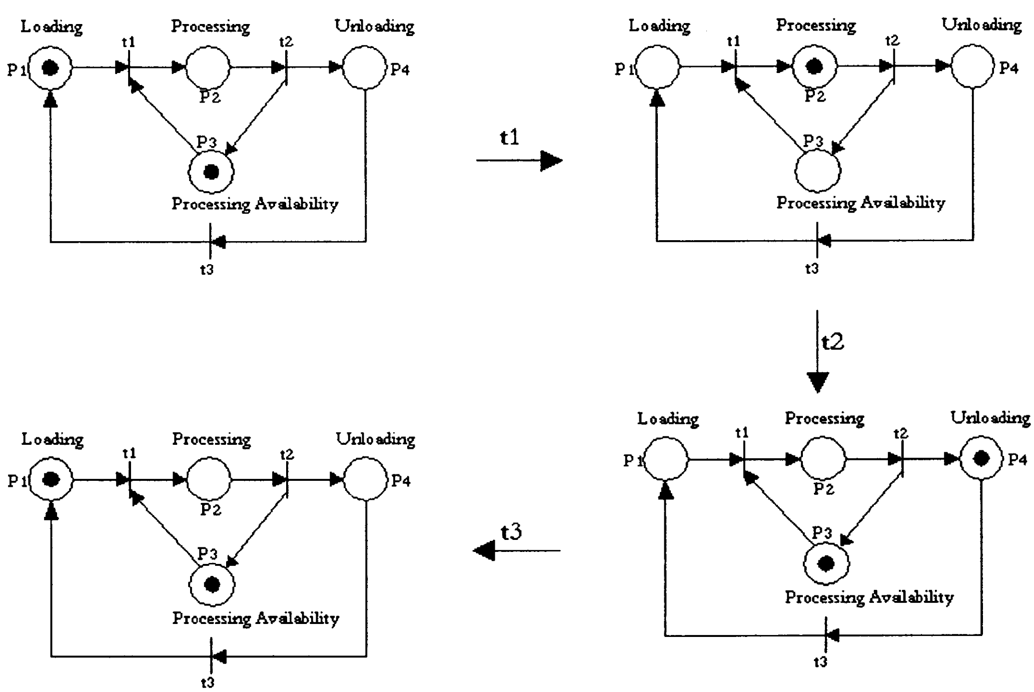


Figure 6.2 Transition of tokens, which is based on enabling and firing rules.

Table 6.1 Reachability Tree for Figure 6.2

State before	Transition	State after
(1,0,1,0)	.T1.>	(0,1,0,0)
(0,1,0,0)	.T2.>	(0,0,1,1)
(0,0,1,1)	.T3.>	(1,0,1,0)

6.3.2 Applications

- Petri nets can be used in the following applications:

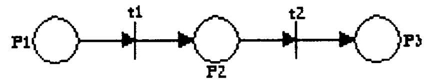
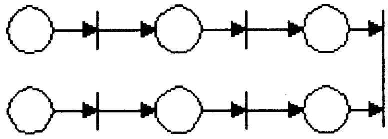
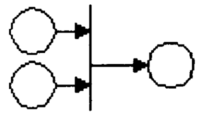
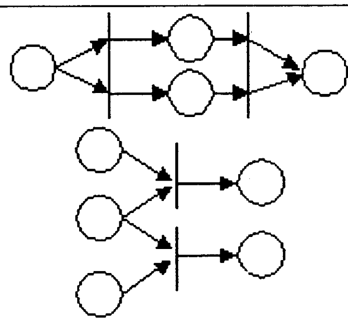
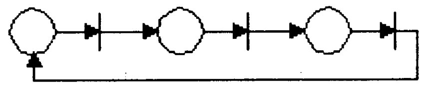
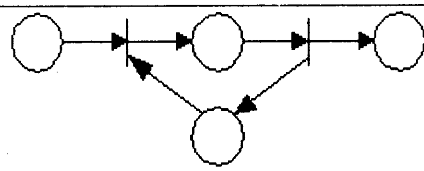
Manufacturing, production, and scheduling systems

- For sequence control, both modeling and visualization and generating the code for a (PLC)
- Communication protocols and networks
- An alternative to finite state machines and state diagrams

6.4 Modeling Methods

The basic relationships between processes in any automated manufacturing line and their representation by PN can be classified as shown in Table 6.2, which shows the modeling method, definition of that method.

Table 6.2 Manufacturing Processes and Their Applications by PN

Method	Definition	Representation
Sequential	If one operation follows the other	
Concurrent	If two operations are initiated by an event	
Dependency	Transition requires two inputs	
Conflict	If either of two operations can follow an operation	
Cyclic	If the sequence of operations follow one after another, and the completion of the last fires the first	
Mutually Exclusive (Synchronization)	Machine can process one part at once resource Sharing	

One of the major advantages of Petri nets is their ability to analyze a system for properties related to manufacturing control. These properties include boundedness or safeness, liveness, and reversibility. Their significance to manufacturing systems is as follows:

1- Boudedness or safeness implies the absence of capacity overflows, which assures there is no overflow. Safeness is a special case of 1-boundedness

2- Safeness of a resource place indicates the availability of only a single resource

3- Liveness implies the absence of deadlock; this property guarantees that a system can successfully produce tokens

4- Reversibility implies the cyclic behavior of a system; it means the system can be initialized from any reachable state

For Petri net, there are conditions that have to be furnished to understand the analysis of modeling and analysis of reachability tree. The latter is considered to be an important tool for the following conditions:

1- If all the places have one token at any firing stage, which means the system is 1. Bounded and safe.

2- If the system continues to produce tokens, that means the system is live.

3- If from any reachable state the system can be initialized, that means the system is reversible.

6.5 Case Study: Modeling and Analysis of PN for NJIT FMS

6.5.1 Description and Modeling

The material handling system of NJIT FMS cell was modeled using Petri net. The modeling is shown in Figure 6.3 and the description of its places and transitions is shown in table 6.3. Table 6.4 shows the reachability tree for material handling system

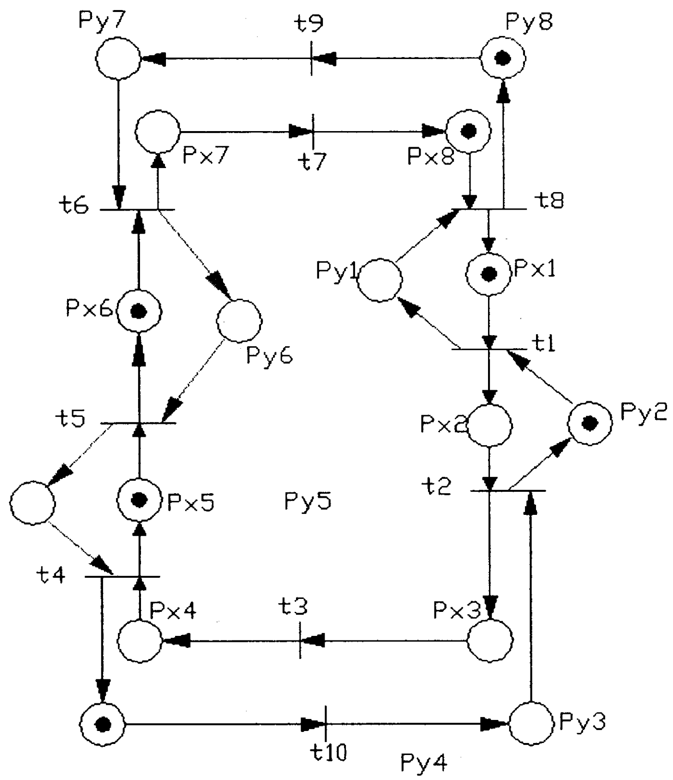


Figure 6.3 PN modeling for a material handling system.

Table 6.3 Places (Events) and Transitions for Material Handling System

Event	Description	Event	Description
Px1	Cart available at the loading station X1	Py1	Availability of cart halting position at X1
Px2	Cart halting at position X2	Py2	Availability of cart halting position at X2
Px3	Cart loaded on the transfer table TT1at X3	Py3	Availability of TT1 at position X3
Px4	Cart transported to position X4 by TT1	Py4	Availability of TT1 at position X4
Px5	Cart available at drilling workstation at X5	Py5	Availability of cart halting position at X5
Px6	Cart halting at position X6	Py6	Availability of cart halting position at X6
Px7	Cart loaded on the transfer table TT2at X7	Py7	Availability of TT2 at position X7
Px8	Cart transported to position X8 by TT2	Py8	Availability of TT2 at position X8
t1	Cart moving from loading station to X2	t6	Cart being loaded on transfer table TT2
t2	Cart being loaded on transfer table TT1	t7	TT2 and the loaded cart move together to X8
t3	TT1 and the loaded cart move together to X4	t8	Cart unloads from TT2 and moves to X1
t4	Cart unloads from TT1 and moves to drilling station	t9	Moves back from position X8 to X7
t5	Cart moves from drilling station to X6	t10	TT1 moves back from position X4 to X3

Table 6.4 Reachability Tree of PN Modeling for Material Handling System

Firing	Transition enabled	P x1	P y1	P x2	P y2	P x3	P y3	P x4	P y4	P x5	P y5	P x6	P y6	P x7	P y7	P x8	P y8
	Initially	1	0	0	1	0	0	0	1	1	0	1	0	0	0	1	1
1	t1	0	1	1	0	0	0	0	1	1	0	1	0	0	0	1	1
	t9														1		0
	t10						1		0								
2	t2			0	1	1	0										
	t6											0	1	1	0		
	t8	1	0													0	1
3	t3					0		1									
	t5									0	1	1	0				
	t7													0		1	
	t9														1		0
4	t1	0	1	1	0												
	t4							0	1	1	0						
	t6											0	1	1	0		
5	t5									0	1	1	0				
	t8	1	0													0	1
	t7													0		1	
	t10						1		0								
6	t2			0	1	1	0										
	t9														1		0
7	t1	0	1	1	0												
	t3					0		1									
	t6											0	1	1	0		
8	t8	1	0													0	1
	t7													0		1	
	t4							0	1	1	0						
9	t5									0	1	1	0				
	t9														1		0
	t10						1		0								
10	t2			0	1	1	0										
	t6											0	1	1	0		
11	t1	0	1	1	0												
	t3					0		1									
	t7	Enabled if and only if t8 is enabled first															
12	t8	1	0													0	1
	t7													0		1	
	t4							0	1	1	0						
13	t5									0	1	1	0				
	t9														1		0
	t10						1		0								
14	T2			0	1	1	0										
	T6											0	1	1	0		

The PN modeling for the milling machine, GE P-50 robot, vision system and part presentation station (Feeder) the modeling is shown in Figure 6.4 and description of places and transition for this system is shown in table 6.5. Its reachability tree is shown in table 6.6.

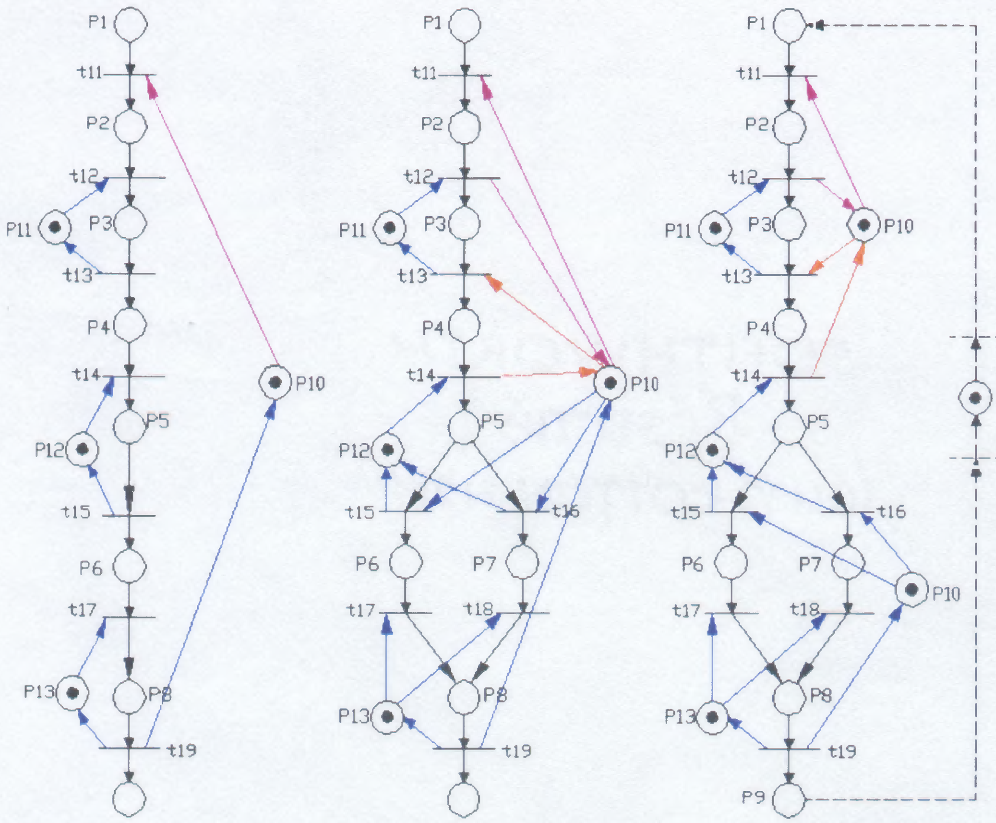


Figure 6.4 Modeling for milling machine, GE P-50 robot, vision system and Part presentation station (Feeder).

Table 6.5 Places (Events) and Transitions for Milling Machine, GE P-50 Robot, Vision System and Part Presentation Station (Feeder)

Event	Description
P1	Raw material to be processed with the cart
P2	Milling machine loaded with raw material by GE P-50 robot
P3	Milling operation performed on the raw material
P4	Finished part returned to the cart
P5	Part inspected by vision camera
P6	The robot places the accepted part in a bin
P7	The robot places the rejected part in another bin
P8	The robot loads the cart with a new blank part
P9	Cart available to be released to the system
P10	GE P-50 robot available
P11	Milling machine available
P12	Vision system available for inspection purpose
P13	Raw material from the parts presentation station
t'	Are added to check this subnet for its properties
t"	
p'	

Table 6.6 Reachability tree of PN Modeling for CNC Milling Machine, GE P-50 Robot, Vision System, and Part Feeder

Firing	Transition enabled	P'	P 1	P 2	P 3	P 4	P 5	P 6	P 7	P 8	P 9	P 10	P 11	P 12	P 13
	Initially	1	0	0	0	0	0	0	0	0	0	1	1	1	1
1	t'	0	1	0	0	0	0	0	0	0	0	1	1	1	1
2	t11	0	0	1	0	0	0	0	0	0	0	0	1	1	1
3	t12	0	0	0	1	0	0	0	0	0	0	1	0	1	1
4	t13	0	0	0	0	1	0	0	0	0	0	0	1	1	1
5	t14	0	0	0	0	0	1	0	0	0	0	1	1	0	1
6	t15	0	0	0	0	0	0	1	0	0	0	0	1	1	1
7	t16	0	0	0	0	0	0	0	1	0	0	0	1	1	1
8	t17	0	0	0	0	0	0	0	0	1	0	0	1	1	0
9	t18 = t17	0	0	0	0	0	0	0	0	1	0	0	1	1	0
10	t19	0	0	0	0	0	0	0	0	0	1	1	1	1	1
12	t"	1	0	0	0	0	0	0	0	0	0	1	1	1	1

Figure 6.4 shows from right to left the modeling made to reduce the number of arcs and places so that the model become marked to facilitate study and analyze the reachability tree.

The PN modeling for the drilling station is shown in Figure 6.5 and the description for the places and transitions is presented in table 6.7. Table 6.8 shows the reachability tree for drilling station

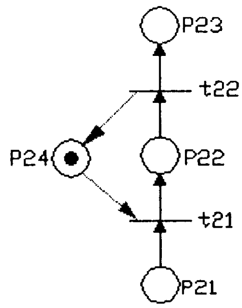


Figure 6.5 Modeling for drilling station.

Table 6.7 Places (Events) and Transitions for Drilling Station

Event	Description
P21	Raw material available with a cart
P22	Drilling operation performed on the raw material
P23	Finished part available with a cart
P24	Drilling machine available
t21	Initiation of drilling operation
t22	Completion of drilling operation

Table 6.8 Reachability Tree of PN Modeling for Drilling Station

Firing	Transition enabled	P'	P 21	P 22	P 23	P 24
	Initially	1	0	0	0	1
1	t'	0	1	0	0	1
2	t21	0	0	1	0	0
3	t22	0	0	0	1	1
4	t"	1	0	0	0	1

The PN modeling for the chamfering station, GMF M1 robot, and 100-tool crib, is shown in Figure 6.6, and the description for the places and transitions is presented in table 6.9. Its reachability tree is presented in table 6.10.

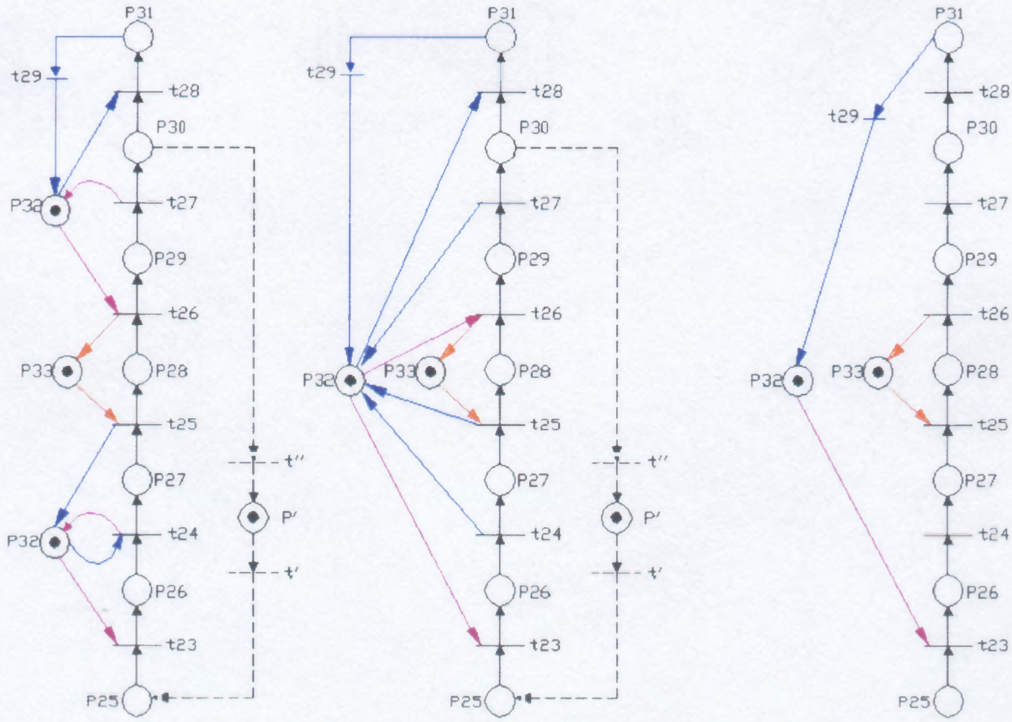


Figure 6.6 Modeling for chamfering station.

Table 6.9 Places (Events) and Transitions for Chamfering Station

Event	Description
P25	Drilled part is available
P26	Loading chamfering machine with the tool
P27	Loading machine with the part
P28	Process chamfering operation
P29	Unload part after operation is finished
P30	Part is available to be released to the system
P31	Unload tool after operation is finished
P32	GMF M1robot is available
P33	Chamfering machine center is available
t'	
p'	Are added to check this subnet for its properties
t"	

Table 6.10 Reachability Tree of PN Modeling for Chamfering Station, GMF M1 Robot, and a 100-Tool Crib

Firing	Transition enabled	P'	P 25	P 26	P 27	P 28	P 29	P 30	P 31	P 32	P 33
	Initially	1	0	0	0	0	0	0	0	1	1
1	t'	0	1	0	0	0	0	0	0	1	1
2	t23	0	0	1	0	0	0	0	0	0	1
3	t24	0	0	0	1	0	0	0	0	1	1
4	t25	0	0	0	0	1	0	0	0	1	0
5	t26	0	0	0	0	0	1	0	0	0	1
6	t27	0	0	0	0	0	0	1	0	1	1
7	t28	0	0	0	0	0	0	0	1	0	1
	t"	1	0	0	0	0	0	0	0	0	1
8	t29	1	0	0	0	0	0	0	0	1	1
	t'	0	1	0	0	0	0	0	0	1	1

Figure 6.6 shows from left to right the modeling modification made to reduce the number of arcs and places so that the model become marked to facilitate study and analyze the reachability tree. The final Petri net model for the entire FMS cell is shown in Figure 6.7.

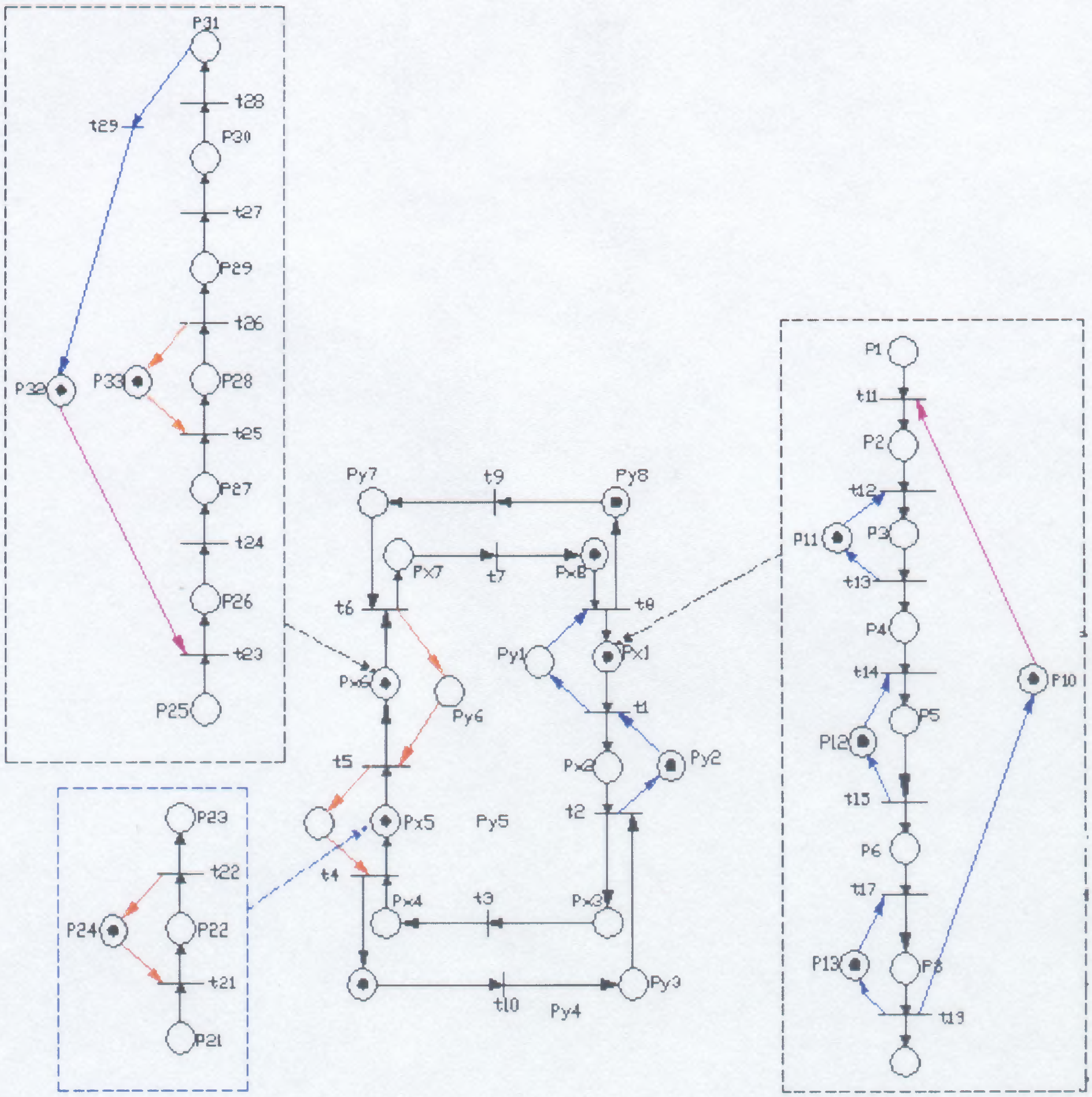


Figure 6.7 Final Petri net modeling for NJIT FMS cell.

A Petri net model can be developed for a manufacturing system given a list of machines, a list of operations, and their relations. The modeling procedure is as follows:

1. A simple Petri net first chosen which describes the aggregate level system and satisfies the safeness, liveness, and reversibility conditions.
2. Stepwise refinement of this PN is done in a manner which maintains the

structural properties while adding process and control details.

3. Stepwise refinement is accomplished by replacing places by basic design modules that describe more detailed logic for the process represented by that place. These basic modules are defined as sequence PN, parallel PN, conflict PN, and mutually exclusive PN.

4. If this method is used, the desirable detail will be achieved and the structural properties guaranteed.

6.5.2 Analysis

It can be noticed that:

- Since each marking has its element being 0 or 1, the net is safe.
- Since the reachability graph has a directed circuit containing all the transitions at least once, the sub.net is consistent.
- From any marking in the reachability graph, any transition can be enabled by an appropriate firing sequence. Thus, the sub.net is live.
- Since every node in the reachability graph is a directed circuit containing node m_o the sub.net is reversible with respect to an initial marking.

6.6 Petri Nets (PNs) Vs Programmable Logic Controllers (PLCs)

PNs and PLCs can be compared in terms of design complexity and response time. The criteria and the factors needed to make the comparison are shown in Figure 6.8.

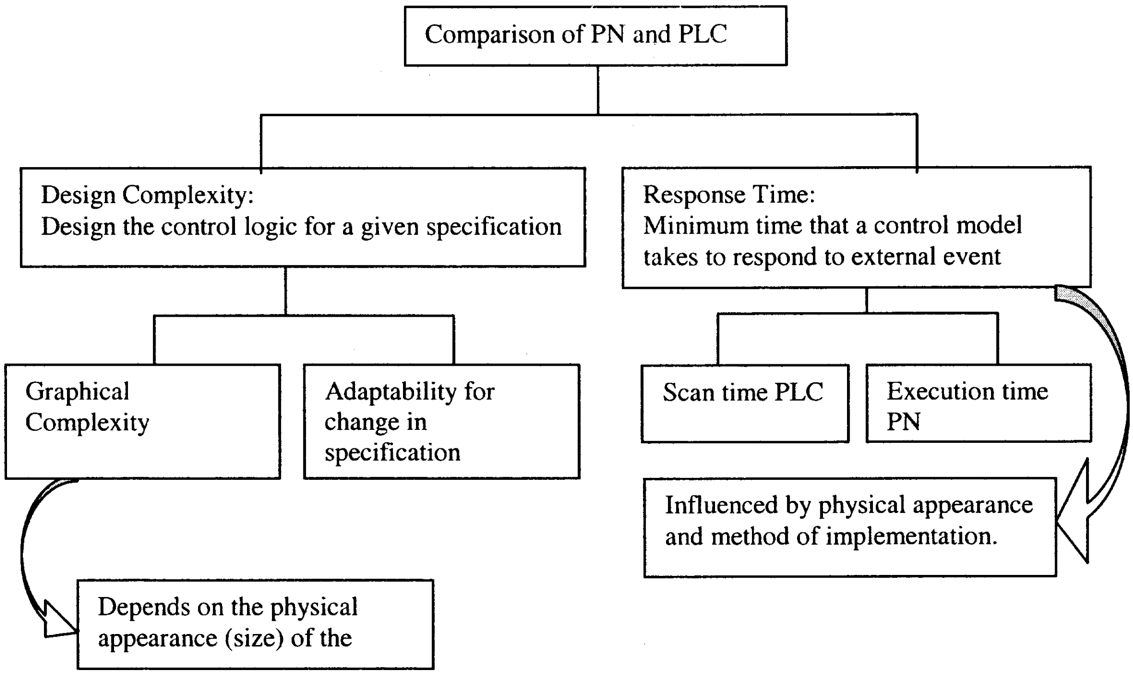


Figure 6.8 Comparison between PN and PLC.

6.7 Comparison of Ladder Logic Diagram (LLD) with PN

There are many factors that should be taken into consideration before making a decision between LLD and PN. An important factor is the length of the model. Shorter models are preferred to use rather then longer models because it's easier to:

- ✓ Understand
- ✓ Check
- ✓ Diagnose
- ✓ Maintain
- ✓ Less time to enter to the controller
- ✓ Less memory used
- ✓ Faster in response

- ✓ Low cost
- ✓ Less design complexity.
- ✓ Adaptability to change in specifications

Table 6.11 makes a comparison between PN with LLD, on the basis of some key factors.

PN presentation for sequences of LLD is shown in appendix H

Table 6.11 Comparison of PN and LLD

Factors	LLD	PN
1. Easiness of readability, understandability, and reliability	• The same node may appear multiple times	No repetition for any node.
2. .Improvement in modifiability and maintianbility	• Need more basic elements to model timers and counters	No modeling for timers and counters
3. Easiness of modeling and simulation	• Lack of ability to know the properties of the system before implementation.	Ability to analyze and check the properties for the system.
4. Debugging of the control logic	• Difficult; because a node appears more than one time in the diagram, so the tracking of control becomes difficult.	Easy, it helps to track the system dynamically
5. Software availability	• Excellent, standard industry practice	Poor; no commercial software.
6. Error handling and diagnostics	• Excellent 1. Methodology in place to handle timeout errors 2. Can include unexpected event error 3. Minimum programming for diagnostics	Poor 1. Error handling is additional. 2. Has no methodology.

CHAPTER 7

CONCLUSIONS

This research accomplished the following:

- Utilized and implemented industrial engineering principles that are used in Flexible Manufacturing Systems.
- Applied in an industrial setting of the components used for operations and control.
- Modeled the FMS workcell control process using Petri net approach.
- Integrated Petri net controllers and programmable logic controllers using a unique control system.

Automated manufacturing improvements will continue to satisfy the demands of industry. These efforts will make the manufacturing more efficient and flexible. These improvements can be in management, control systems, modeling and simulation, scheduling and operations, manufacturing processes, and cost reduction techniques. Those, who are interested in this subject, can be confident that these manufacturing principles will be adoptable to any change, flexible to any industry and feasible for any cost.

APPENDIX A

FMS DRAWINGS SHOW NJIT FMS

The five figures that follow show the layout of NJIT FMS cell from different views. They are drawn by AutoCAD r14

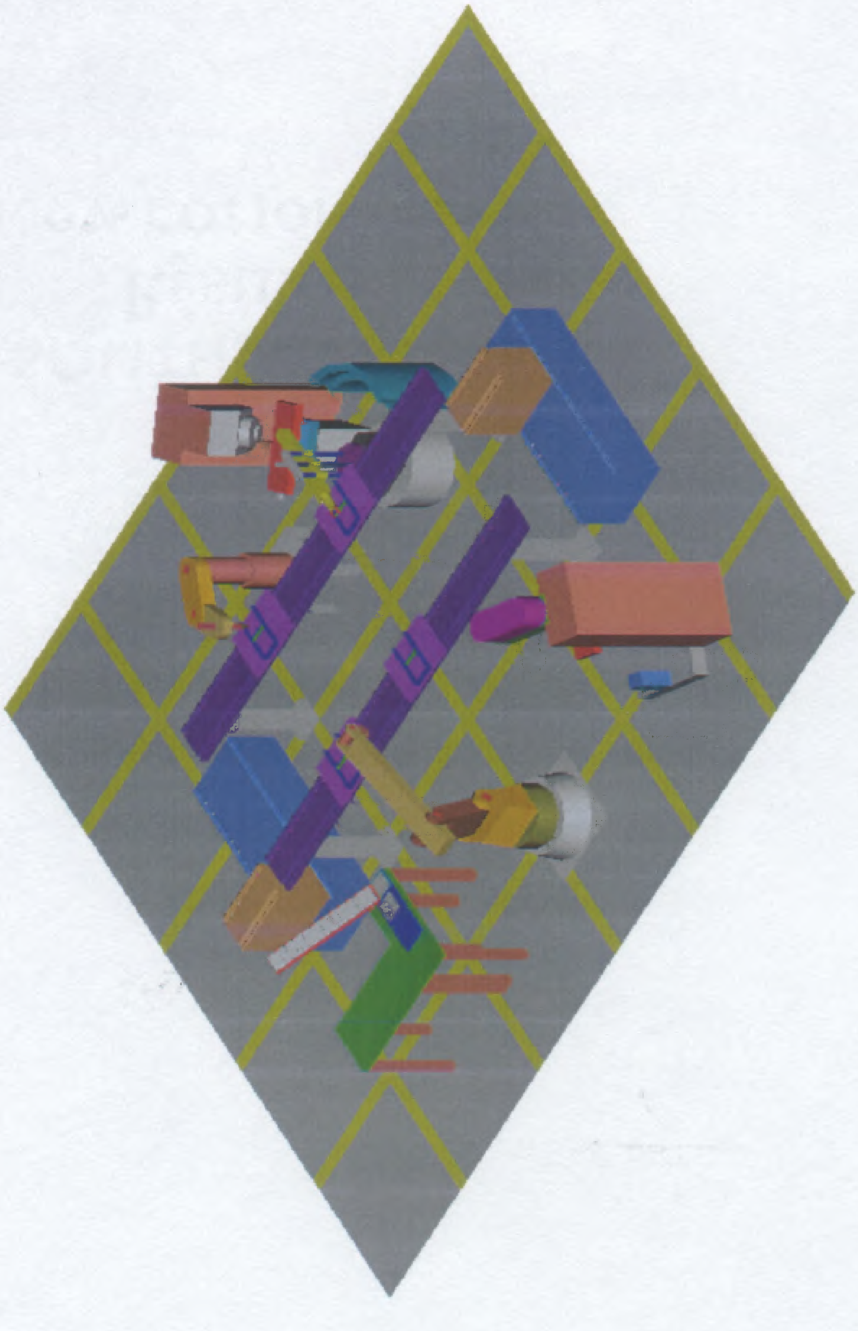


Figure A.1 NJIT FMS SE isometric view.

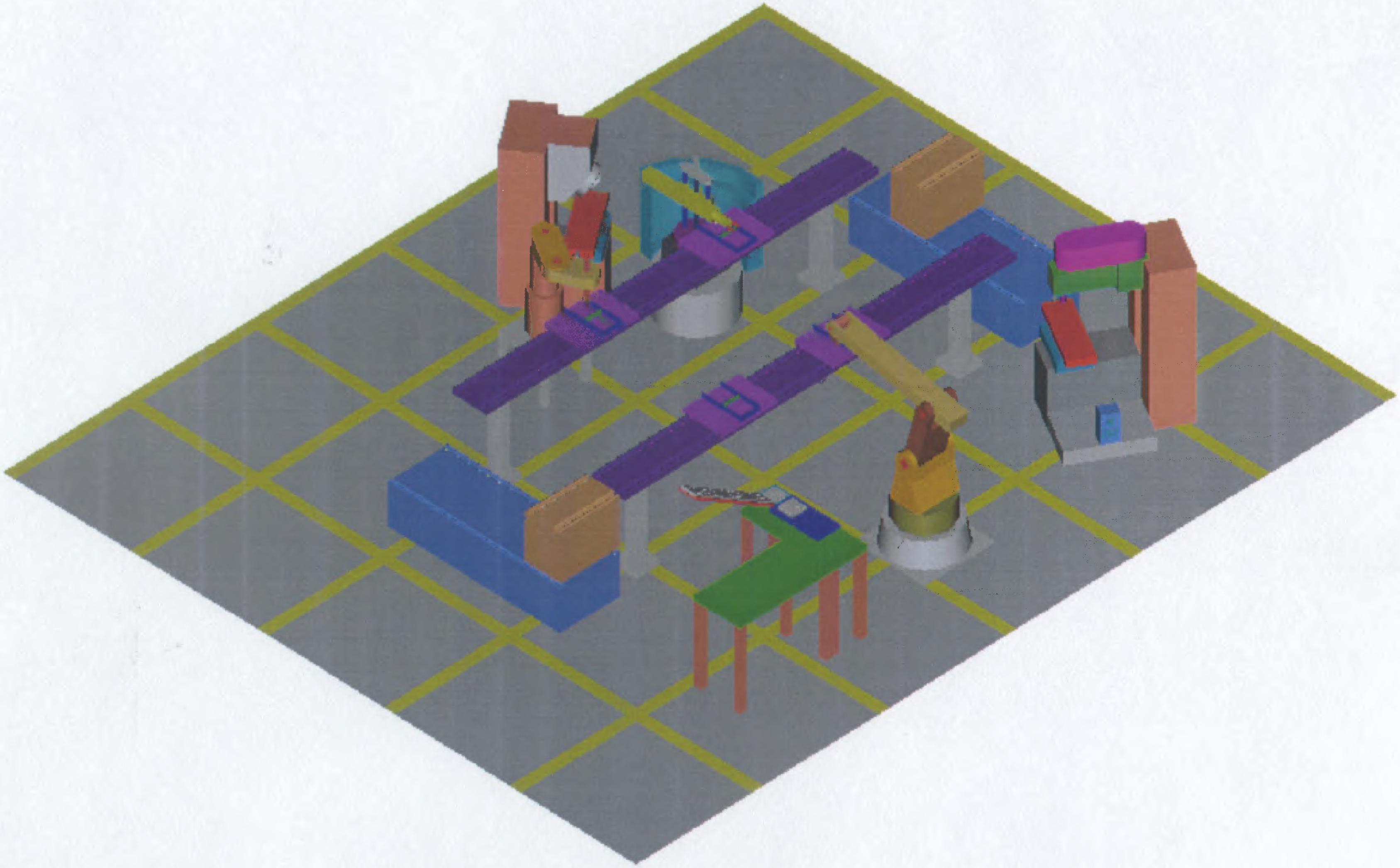


Figure A.2 NJIT FMS layout SW isometric view.

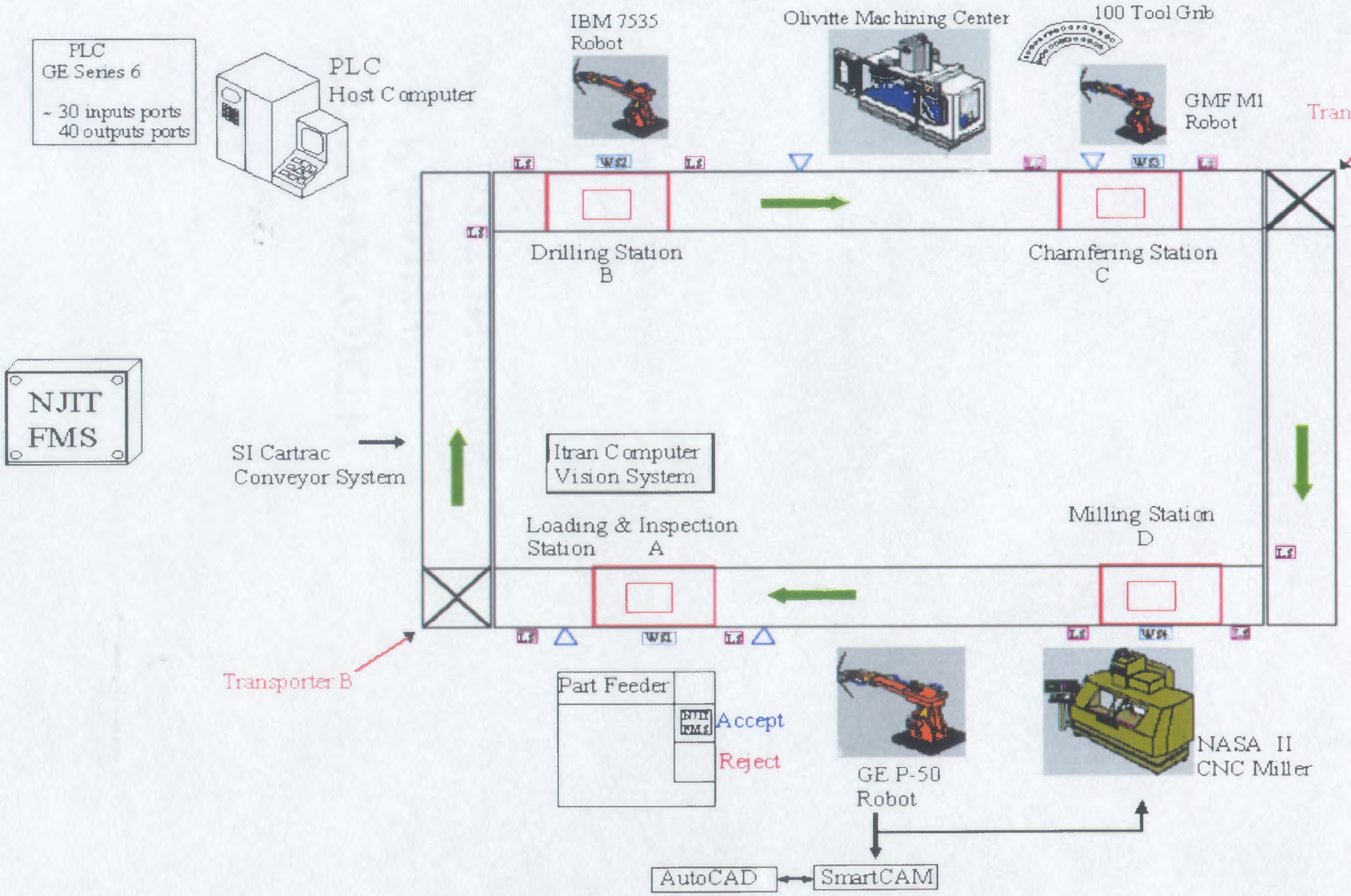


Figure A.3 Schematic diagram for NJIT FMS.

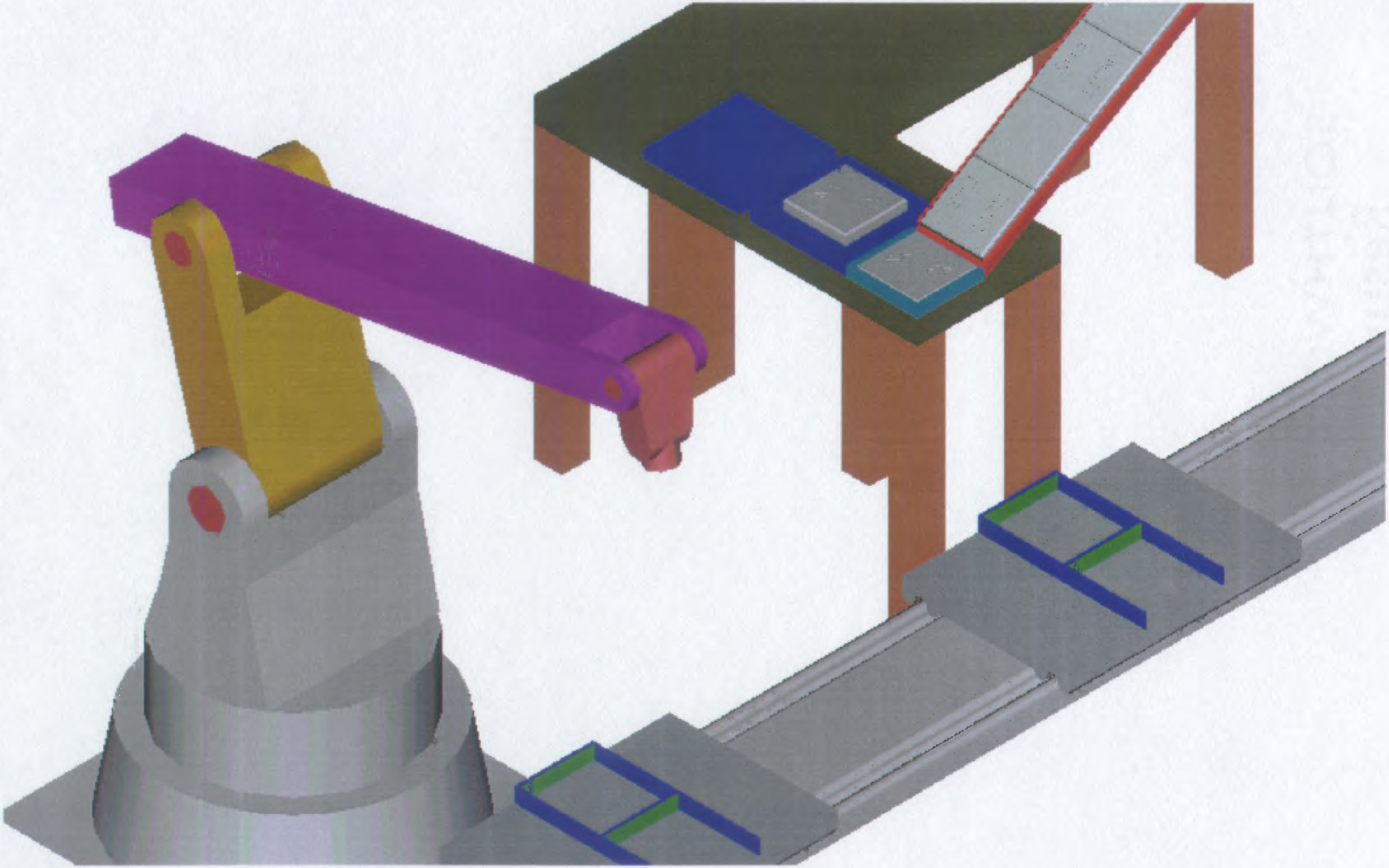


Figure A.4 Loading/unloading process station.

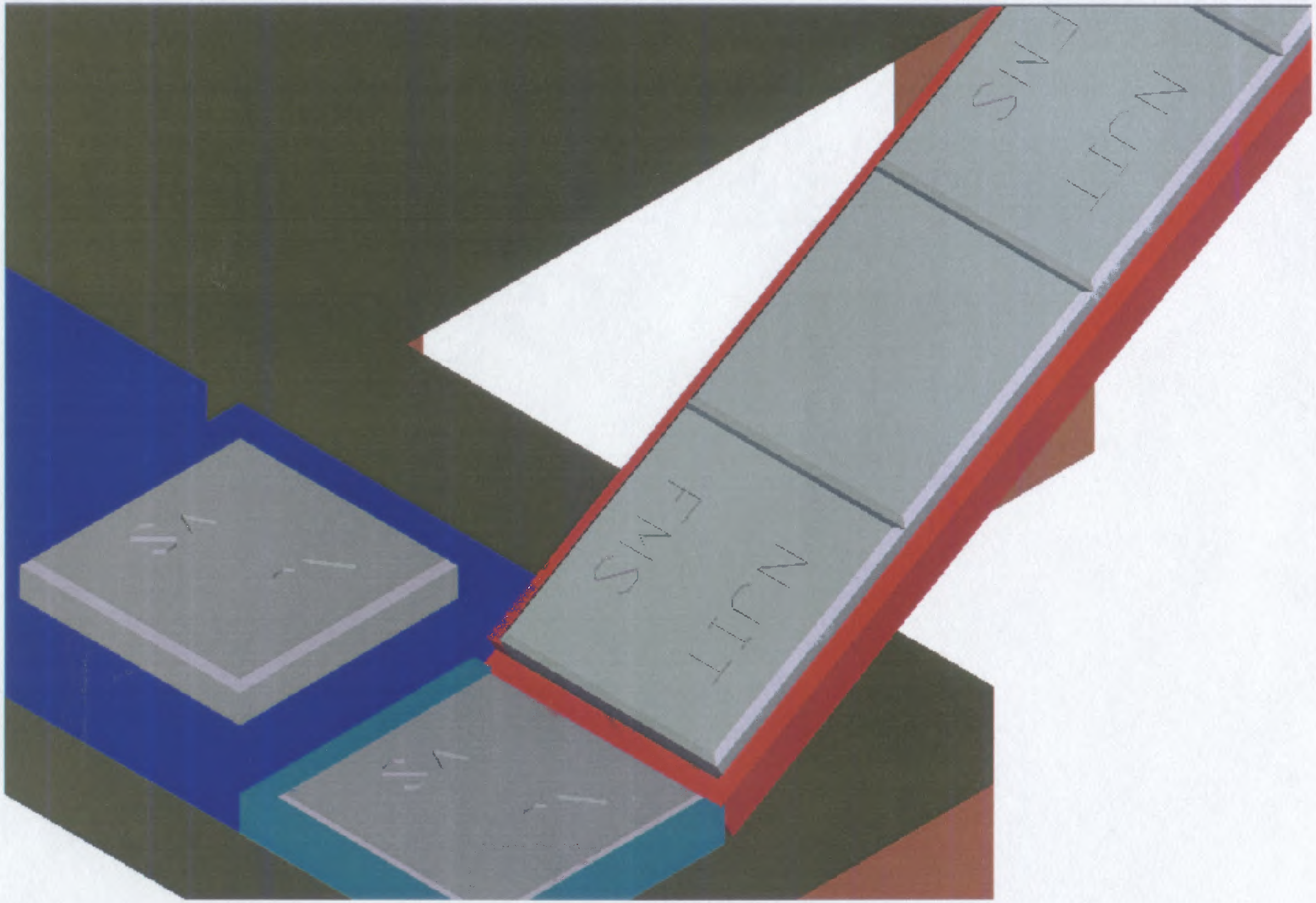


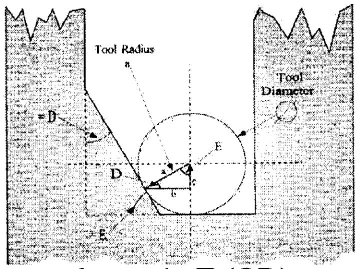
Figure A.5 Feeder with the parts.

APPENDIX B

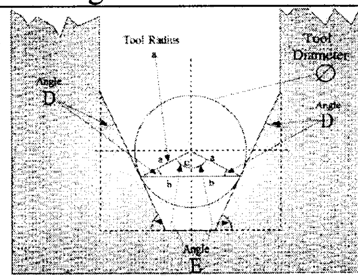
FORMULAS THAT CAN BE USED FOR CNC PROGRAMMING

In the table below, there are formulas that can be utilized in CNC programming

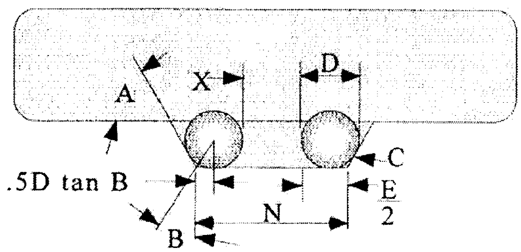
Table B.1 Formulas that can be Used for CNC Programming

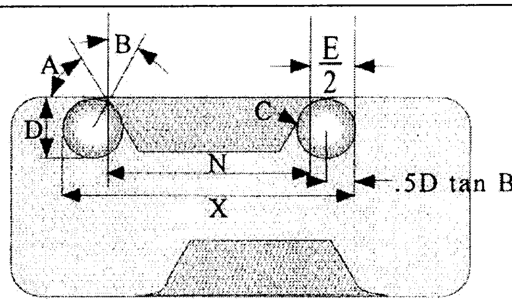
<table>
<tr>
<td>

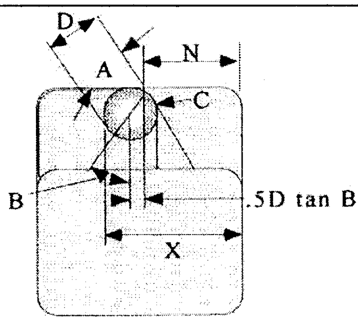
$b = a \sin E$ (OR) $\csc E$

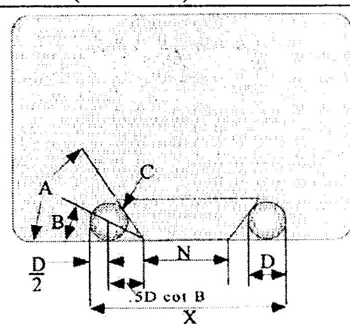
$c = a \cos E$ (OR) $\frac{a}{\sec E}$</td>
<td>

$b = a \sin E$ (OR) $\frac{a}{\csc E}$

$c = a \cos E$ (OR) $\frac{a}{\sec E}$</td>
</tr>
<tr>
<td>

$E = D(1+\tan B)$ $X = N.E$</td>
<td>

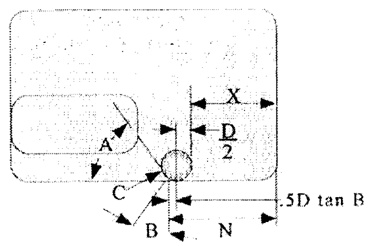
$E = D(1+\tan B)$ $X = N+E$</td>
</tr>
<tr>
<td>

$F = 0.5D(1+\tan B)$ $X = N+F$</td>
<td>

$G = D(1+\cot B)$ $X = N+G$</td>
</tr>
</table>

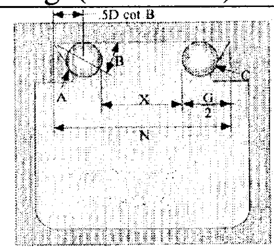
Table B.1 Formulas that can be Used for CNC Programming. (Continued)

<table>
<tr>
<td>



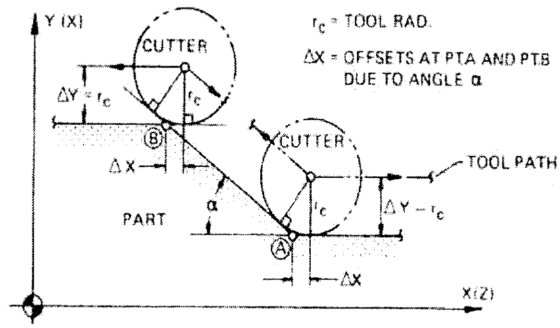
$F = 0.5D(1+\tan B) \qquad X = N.F$

</td>
<td>



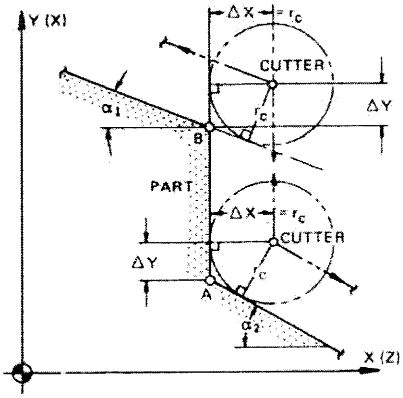
$G = D(1+\cot B) \qquad X = N.G$

</td>
</tr>
<tr>
<td>



$\Delta Y = a_{rc} \qquad \Delta X = a_{rc}.\tan \alpha/2$

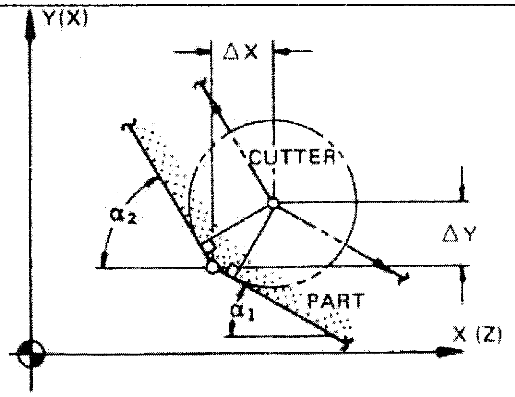
</td>
<td>



$\Delta X = a_{rc}$ (A) $\Delta Y = a_{rc}.\tan(45 . \frac{\alpha 2}{2})$

(B) $\Delta Y = a_{rc}.\tan(45 . \frac{\alpha 1}{2})$

</td>
</tr>
<tr>
<td>



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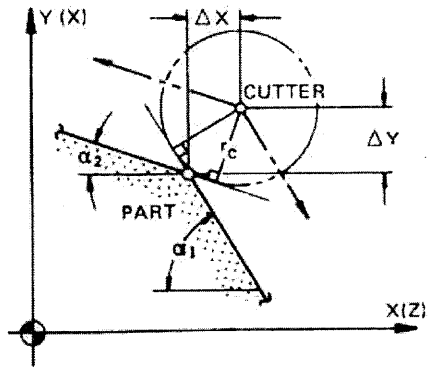
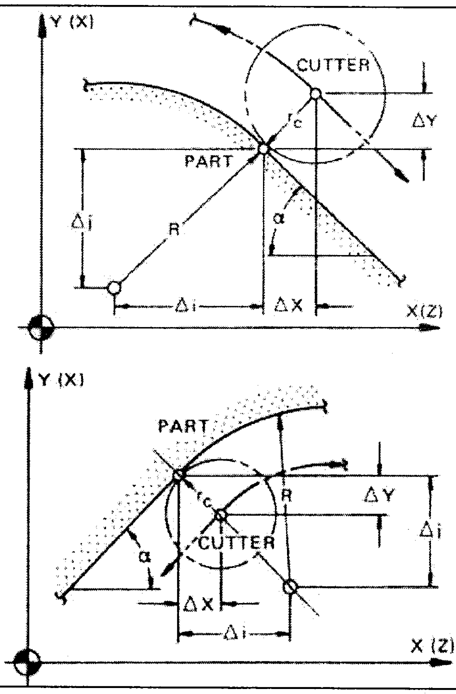


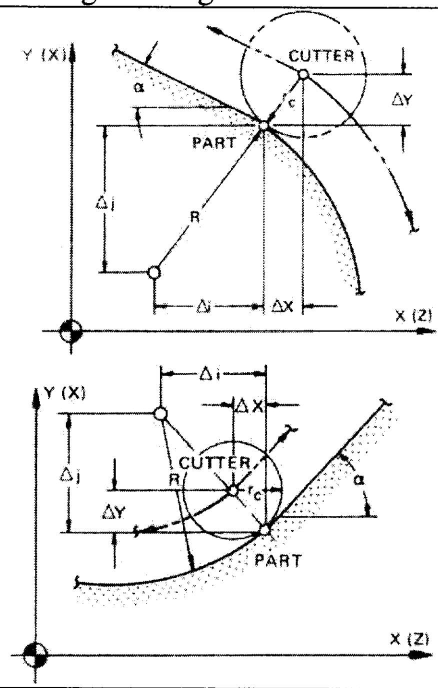
</td>
</tr>
<tr>
<td colspan="2">

$$\Delta X = r_c \frac{\sin(\frac{\alpha 1+\alpha 2}{2})}{\cos(\frac{\alpha 2-\alpha 1}{2})} \qquad \Delta Y = r_c \frac{\cos(\frac{\alpha 1+\alpha 2}{2})}{\cos(\frac{\alpha 2-\alpha 1}{2})}$$

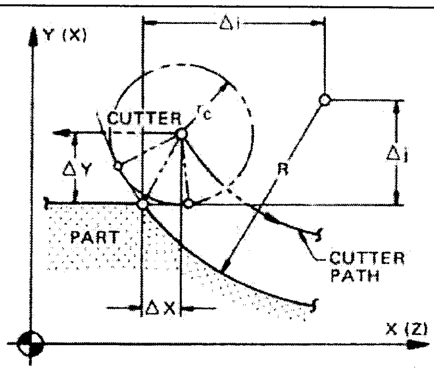
</td>
</tr>
</table>

Table B.1 Formulas that can be Used for CNC Programming



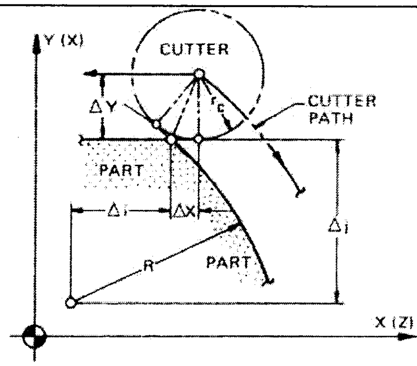


$$\Delta X = a_{rc} . \sin \alpha \qquad \Delta Y = a_{rc} . \cos \alpha$$



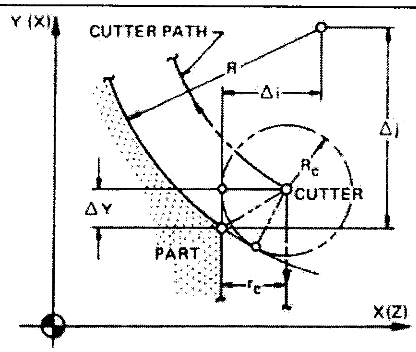
$$\Delta Y = a_{rc}$$

$$\Delta X = \Delta i - \sqrt{(R - r_c)^2 - (\Delta j - r_c)^2}$$



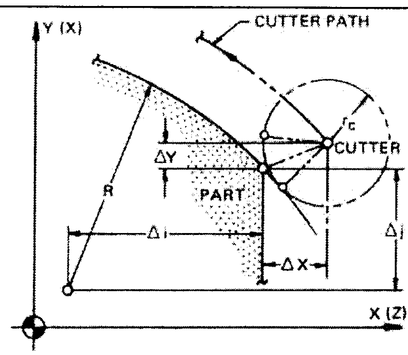
$$\Delta Y = a_{rc}$$

$$\Delta X = \sqrt{(R + r_c)^2 - (\Delta j + r_c)^2} - \Delta i$$



$$\Delta X = a_{rc}$$

$$\Delta Y = \Delta j - \sqrt{(R - r_c)^2 - (\Delta i - r_c)^2}$$



$$\Delta x = a_{rc}$$

$$\Delta Y = -\sqrt{(R + r_c)^2 - (\Delta i + r_c)^2} - \Delta j$$

APPENDIX C

DRILLING AND MILLING OPERATIONS PROGRAM

The following table shows the programming for drilling and milling operations done by CNCez software. It also shows the data preparation for CNC programming

Table C.1 Drilling and Milling Program

Programming of DRILLING Operation									
Sequence number (N)	**Preparatory functions (G)**	**X**	**Y**	**Z**	**S**	**T**	**F**	**M**	**Notes**
5	90, 20, 00								G00: Rapid Positioning G20: Input in inch G90: Absolute programming
10						1		06	T1: 1/8" slot drill M06: Tool Change
15					1200			03	M03: Spindle on cw
20	00								G00: Positioning in Rapid
25	01	0.5	0.5						G01: Linear Interpolation
30				2.1					
35				1					
40		6.5							
45				2.1					
50				0.5					
55			6.5						
60				2.1					
65				0.1					
70		0.5							
75				2.1					
80				0.5					
85	00	00	00						
90								05	M05: Spindle Off
Programming of MILLING Operation									
95	20, 91								G20: Input in Inch G91: incremental programming
100						3		06	T3: ¼" end mill
105					900			03	
110		0.5	3.5						
115				0.75			5		
120			2.0				20		
125		1	2						
130			2						
135				1.25					
140		1							
145				1.25			5		

Table C.1 Drilling and Milling Program (Continued)

150		1					20		
155		0.5							
160			1.5						
165	02	1							G02: circular interpolation cw R = 0.5 inch
170	01			1.25					
175		2	1.5						
180				1.25			5		
185		1					20		
190		0.5							
195			2						
200		0.5							
205		1							
210				1.25					
215		1.5	2						
220				1.25			5		
225		1					20		
230		0.5							
235			2						
240				1.25					
245	00								
250	90	00	00						
255	91	0.75	1						
260				1.25				5	
265	01		2				20		
270		1.5							
275				1.25					
280		1.5	1						
285				1.25					
290		1							
295				1.25					
300		1	1						
305				1.25			5		
310			2				20		
315		0.75	.2						
320		0.75	2						
325			2						
330				1.25					
335		2	2						
340				1.25			5		
345		1					20		
350	03		1						G03: Circular interpolation ccw J = .0.5
355	01	0.5							
360	02		1						J = .0.5
365	01	1							
370				1					
375	90								G90: Absolute units programming
380		0	0						
385								30	M30: Exit of program. Jump to start

APPENDIX D

CREATING A SIMPLE ROBOT BY USING WORKSPACE3

The following tutorial is designed to match the interests between Robotics and CAD. A broad understanding of the principles of CAD and robotics interfacing can be achieved from this tutorial. It is about creating small robot structure using Worksape^{TM}3.

Simple Tutorial

Create cylinder (create menu)
use default name, radius=100, default length and region
create box (create menu)
use name = link1, length = 40, length2= 400, length3=40
click on the front view icon
click on the move object icon
drag LINK1 using the mouse with the mouse button pressed down to just above CYLINDER, and move a little to the left so that rightmost part of LINK1 is just to the right of the center of the CULINDER }
click on the copy object icon
use the default name (LINK2)
click on the move object icon and drag LINK2 to just above LINK1 so that the rightmost part of LINK2 is just to the right of the leftmost part of LINK1
click the mouse over the CYLINDER and then click on the snap onto object icon
the flesh of the robot is now modeled and the base of the robot is highlighted
create robot (create icon)
enter 2 for the number of joints
click on the top view icon
the direction of the rotation of the first joint is shown as an arrow, leave this joint in its default position
click the mouse over LINK1 and then click on the snap onto object icon
move Axis (Edit joint submenu of the layout menu)
drag the axis using the mouse with the mouse button pressed down to the intersection of LINK1 and LINK 2
click the mouse over LINK2 and then click on the snap onto object icon
move axis (edit joint submenu of the layout menu)
drag the axis using the mouse button pressed down to the end of LINK2
click on the diagonal view icon

the robot is fully defined and may now be moved
show kinematics (edit robot submenu of the layout menu)
the joint distances and the offsets are labeled on the screen
exact kinematics (edit robot submenu of the layout menu)
select the 2R inverse kinematics template
the A matrix constant (the mathematics representation of how the robot moves) for the robot are shown
click OK
a massage amperes saying math achieved with the inverse kinematics for the 2R inverse kinematics is now available for the this robot (it can now be moved by specifying robot endpoint positions)
click on the top menu icon
pendant
change the joint one variable by moving the mouse over the up/down button on the pendant and pressing the mouse button down
repeat with joint 2
follows (Pendant menu)
click the mouse at different points near the end point of the robot
the robot moves to each position instantly or comes up with a massage explaining that the robot cannot achieve the position.
move home (action menu)
the robot moves smoothly to its home position
CP move (action menu) the robot moves smoothly to the current pointer.
move home (action menu)
the robot returns to the home position

APPENDIX E

INPUT AND OUTPUT PORTS USED IN PLC TO CONTROL THE FMS

The tables that follow show the input and output lists and their ports and nicknames for the PLC controller used in NJIT FMS cell for the process stations and IBM 7535 and GE P-50 robots.

Table E.1 Input List

Input List		
1. Load/Unload Station		
DESCRIPTION	***I/O Ports***	***Nickname***
Limit Switch 302 car present at transfer station #1	10001	LS302
Limit Switch 303 transporter #1 at home position	10002	LS303
Limit Switch 304 transporter #1 at away position	10003	LS304
Limit Switch 305 transfer of cart clear of transporter #1	10004	LS305
Photocell contract for cart present transporter #1	10005	PCR201
Limit switch 307 cart present at work station #1	10006	LS307
Limit switch 308 cart present at work station #2	10007	LS308
Normal stop pushbutton	10008	PB155A
Release station #1 pushbutton	10009	PB310
Release station #2 pushbutton	10010	PB313
Limit switch 402 car present at transfer station #2	10013	LS402
Limit Switch 403 transporter #2 at home position	10014	LS403
Limit Switch 404 transporter #2 at away position	10015	LS404
Limit Switch 405 transfer of cart clear of transporter #2	10016	S405
Photocell contract for cart present transporter #2	10017	PCR202
Limit switch 407 cart present at load/unload station.	10018	LS407
Release load/unload station pushbutton	10020	PB4098
System run	10021	
System start pushbutton	10022	
Emergency stop pushbutton air pressure necessary*	10024	
2. CNC Milling Machine		
DESCRIPTION	***I/O Ports***	***Nickname***
Machine tool jog mode	10033	JOGMODE
Machine tool M22	10034	M22

Table E.1 Input List (Continued)

Machine tool M21	10035	M21
M decode spare	10036	
M decode spare	10037	
M decode spare	10038	
M decode spare	10039	
OEM Emergency stop pushbutton	10040	
Optomation Data bit 0	10049	OPT0DB0
Optomation Data bit 0	10050	
Optomation Data bit 0	10051	
Optomation Data bit 0	10052	
Optomation Data strobe	10056	DATASTB
Optomation VPL run	10057	
Optomation Data overflow	10058	
Optomation error	10059	
Optomation over temperature	10060	
2. Robot		
DESCRIPTION	**I/O Ports**	**Nickname**
Robot output #0 – turn on Gripper	10065	GRP ON
Robot output #1 – turn off gripper	10066	GRP OFF
Robot output #2 – close vise	10067	CLSCLMP
Robot output #3 – robot clear of CNC	10068	ROBOTCL
Robot output #4 – open vise	10069	OPENCLP
Robot output #5	10070	Camera#2 take PIX
Robot output #6	10071	
Robot output #7	10072	Robot Release STA #2
Robot output #8	10073	
Robot output #9	10074	
Robot output #10	10075	
Robot output #11	10076	
Robot output #12	10077	
Robot output #13	10078	
Robot output #14	10079	
Robot output #15	10080	Robot in motion
Robot in motion	10081	
Robot abnormal welding condition	10082	
Robot emergency stop	10083	

Table E.2 Output List

Output List		
1. Load/Unload Station		
DESCRIPTION	***I/O Ports***	***Nickname***
Enter transporter #1 solenoid	O0001	SOL331
Exit transporter #1 solenoid	O0002	SOL332
Transporter #1 tube drive forward direction	O0003	MSF334
Transporter #1 tube drive reverse direction	O0004	MSR334
Transporter #1 traffic Q solenoid	O0005	SOL337
Work station #1 solenoid	O0006	SOL340
Work station #2 solenoid	O0007	SOL343
Enter transporter #2 solenoid	O0009	SOL431
Exit transporter #2 solenoid	O0010	SOL432
Transporter #2 tube drive forward direction	O0011	MSF433
Transporter #2 tube drive reverse direction	O0012	MSR434
Transporter #2 traffic Q solenoid	O0013	SOL437
Load/unload solenoid	O0014	SOL440
System normal stop	O0015	STOP
Robot gripper solenoid	O0016	Gripper ON
2. CNC Milling Station		
DESCRIPTION	***I/O Ports***	***Nickname***
Machine tool vise solenoid	O0017	Vise Closed
Machine tool emergency stop	O0033	Emergency
Machine tool feedhold	O0034	Feedhold
Machine tool cycle stop	O0035	
Machine tool cycle start	O0036	Sysstrt
Machine tool M01	O0037	
Optomation system reset	O0052	
3. Vision Inspection Station		
DESCRIPTION	***I/O Ports***	***Nickname***
Car present workstation #1 take picture camera#1	O0049	CARPR1
Reset take picture station #1	O0050	PRTPR2
4. Robot		
DESCRIPTION	***I/O Ports***	***Nickname***
Robot input #0 – Cart present at work station #2	O0065	Go get Part
Robot input #1	O0066	
Robot input #2	O0067	

Table E.1 Input List (Continued)

Robot input #3	O0068	
Robot input #4	O0069	
Robot input #5	O0070	
Robot input #6	O0071	
Robot input #7	O0072	
Robot input #8	O0073	Accept - reject
Robot input #9	O0074	
Robot input #10	O0075	
Robot input #11	O0076	
Robot input #12	O0077	
Robot input #13	O0078	
Robot input #14	O0079	
Robot input #15	O0080	
Robot job select 2**0	O0081	JOBSEL0
Robot job select 2**1	O0082	JOBSEL1
Robot job select 2**2	O0083	JOBSEL2
Robot job select 2**3	O0084	JOBSEL3
Robot zero point adj. Or servo on	O0085	ZEROADJ
Robot servo off	O0086	SERVOFF
Robot external start	O0087	EXTSTRT
Robot external stop	O0088	
Robot emergency stop	O0089	EESTOP
Part is present station #1	O0190	PRTPRE1
Part is missing station #1	O0191	PRIMIS1
Part is accepted station #2	O0192	PRTACP2
Part is rejected station #2	O0193	PRTREJ2
Robot job #2 selected – Load CNC	O0211	JOB2SEL
Robot job #3 selected – Unload CNC	O0212	JOB3SEL
5. Reloading Station		
DESCRIPTION	***I/O Ports***	***Nickname***
Station #1 Table pointer	O0400	PRTPTR1
Station #1 Table pointer	O0401	PRTPTR2
6. Functions		
DESCRIPTION	***I/O Ports***	***Nickname***
Power UP	O0480	PWERUP
System Enable	O0490	SYSENAB
Initiate	O1024	INIT

APPENDIX F

DESCRIPTION FOR EACH PORT AND SEQUENCE USED IN PLC

Table F.1 describes the sequences used in the ladder logic diagram to control the FMS cell and the names of each sensor and port assigned to each sequence. It also contains some notes after certain sequences to explain further that sequence

Legend NS = No Switch, i.e. software logic
LS = Limit Switch
PB = Push Button
PC = Photocell
SEE # = reference to another outlined logic

Table F.1 Sequences Description for PLC Control Program

Initialization			
Seq. No.	Description	Sensor	Port
1	Initialize registers for vision system and set them to 0 Note: only for new-start when power up not energized	<NS>	O0480
2	System start Check if conveyor locations initialized (i.e. at end positions)	<PB2>	AO0050.
	Latched if system not yet enabled		
	and transfer Tables not in end positions		
	for Home	LS 14, LS14A	
	for away	LS 20, LS 20A	
3	Normal Stop	<PB3>	AO0051
	Latched if normal stop		O0015. after 8 parts
	depressed or system stop		
4	Emergency Stop		O0089
	Energized if emergency–stop	<PB 4>	
5	System Enabled		O0490.
	Energized if "System Run" input Note: (i.e. not Emergency. Stop), and transfer tables located at the end positions. They should be "Home" if they carry no cart, and "away" if they carry A cart	(I0021)	
Initial Inspection Station #1			
Seq. No.	Description	Sensor	Port
6	Release cart from load/unload station		O0014.
	Only if cart present and no cart at inspect STAT.1	<LS 6.1>	
		<LS 6.2>	

Table F.1 Sequences Description for PLC Control Program (Continued)

13	Energized transfer table 1 tube drives “Home”		O0004.
	Only if conveyor initialized	<SEE 2>	
	And no cart on transporter	<PC11>	
14	Cart is Home		AO0101
	Latched 3 sec. After hitting home limit switch	<LS 14>	
15	Cart present at queue 3		AO0107.
	Latched 1.5 sec after having hit. No second cart will be able to enter the queue (mechanic stop).	<LS 10>.	
16	Activate enter Push. Pull solenoid		O0001
	only if : Transfer table home	<LS 14>	
	and no cart on transporter	<PC 11>	
	and cart present OR no cart entered	<LS 10><PC 11>	
	and system enables	<SEE5>	
	and not drive till home		
	and not normal stop OR not O0001 already running.	<SEE 3>	
17	Allow cart to enter transfer table 1		O0005
	(actuator at queue 3 on rear conveyor receives air flow to push mechanical stop aside) only if:		
	transfer table home	<LS14>	
	and Push/Pull active	<SEE 16>	
	and cart in queue 3	<LS 10>	
	and system enabled	<SEE 5>	
	and not normal stop	<SEE 3>	
18	Latch that cart is present on transfer table 1		AO0104
	Note: (Latched with <PC 11> and reflecting tape (on the carts); the tubes drive the cart for another 2 sec. To ensure that it is at the end position: AO0105)		
19	Energize transfer drive (toward “away” position)		O0003.
	Only if conveyor system initialized	<SEE 2>	
	And cart on transporter	<PC 11,SEE18>	

Table F.1 Sequences Description for PLC Control Program (Continued)

20	Signal that table is at "away" position		AO0102.
	Note: (AO0102 is activated by <LS 20>. The tubes are driven for another 3 sec: AO0103)		
21	Energize push/pull solenoid to allow cart to exit to inspection station 2. (Mechanism is depressed in step 11)		O0002
	only if table at away position	<LS 20>	
	and cart on table	<PC 11>	
	and system enabled	<SEE 5>	
	and table not driven	<SEE 20>	
	and no cart at Station 2	<LS21>	
Inspection Station #1			
Seq. No.	Description	Sensor	Port
22	Cart is off table		AO0108
	Latched with transferred table 1 clear	<LS 12>	
23	Count carts existing table (and reset after 4^{th} part)		O0401
	Counted with	<LS 12>	
24	Part present at station 2		O0205
	Only if cart at inspect. Station 2	<LS 21>	
	And optomation result first part present mask	<NS>	
Robot Control Logic			
Seq. No.	Description	Sensor	Port
25	Robot job select permit		AO0129
	only if system enabled	<SEE 5>	
	and robot not in motion	<NS, I00810>	
	and machine tool not in jog mode	<NS, AO0129>	
	and cart at station2	<LS 21>	
Warning: the carts at this point must be empty , the job select permit will automatically initiate the robot to load the first 4 parts.			
26	Rung 58 Logic		
	"Down Counting" from 4 to 0 <LS 21>. When counter = 0. i.e. 4 parts went through the system, the coil "initial 4 parts loaded" (AO0130) is energized and latched		

Table F.1 Sequences Description for PLC Control Program (Continued)

27	All three job selects require that *1*. select Job #0: <LATCHED> *2*. either job #1 : Load initial 4 parts OR Job #3: Unload machine and inspect part *3*. in case of normal system stop command <LS 3, OR part limit> Select Job #2: <LATCHED> Will select job #4, and initiate A "Robot go Home"		O0081
	Power up	<SEE 39>	
	System Enabled	<SEE 5>	
	Robot not in motion	<NS, I0081>	
	Job select permit	<SEE 25>	
Note: After job select, A 250 msec delay will ensure that data was transmitted, and the external start permits O0087 and AO0131 <LATCHED> are sent to the robot controller. The robot's servo motors will be shut off, i.e. the robot disabled, only when the emergency stop <PB 4> is pressed. The zero. adjust O0085 will only occur if servo. off O0086 is recovered by pressing recover <PB 2.1>			
28	Turn gripper on <LATCHED>		
	"ON" with <both received from robot controller output port>		I0065
	"OFF" with <both received from robot controller output port>		I0066
	Only if power up	<SEE 39>	
29	Allow robot to get part		O0065
	only if cart is at station #2	<LS 21>	
30	Accept/reject part <LATCHED>		O0073
	"ON" if part accepted	<SEE38>	O0192
	"OFF" if part rejected	<SEE38>	O0193
	only if system enabled	<SEE 5>	
	and power up	<SEE 39>.	
31	Release cart from station #2		O0007
	Automatic with signal <from robot controller>		I0072
	Manually with →→	<PB 31>	
	→ IF robot not in motion	<NS, I0081>	
32	Select job "load CNC"		O0211
	Latch if not job select 0,2,3	<SEE27>	(O0081, O0083, O0084)
	And job select 1	<SEE 27>	(O0082)
	Unlatch if not power up	<SEE 39>	

Table F.1 Sequences Description for PLC Control Program (Continued)

	OR not system enabled	<SEE 5>	
	OR robot clear of CNC	<SEE 35>	
33	Select job "unload CNC"		O0212
	Latch if Job 0,1	<SEE 27>	(O0081, O0082)
	And not job select 2,3	<SEE 27>	(O0083, O0084)
	Unlatch	<SEE 32>	
Mark Century 1 Interface			
Seq. No.	Description	Sensor	Port
34	In case of emergency stop <PB 4> send Unstop signal to machine tool		O0033
	Robot clear of CNC		AO0150
	Latch if robot sends "Clear" signal to PG.		I0068
	Unlatch (reset) if machine tool send load signal. (Resulting in output AO0151. One shot). Start permit for machine tool not until robot is clear again. <ALL OF THE ABOVE NS>		I0034
35	Machine tool start plus < LATCHED FOR 250 MSEC>		AO0134
	Energized after start signal was energized and subsequently delayed for 1.5 sec. Conditions for start signal AO0137 to be energized:		AO0137
	System enabled	<SEE 5>	
	And Freehold	<NS, O0034>	
	As long as robot clear and no load/unload request)		
	and machine vise closed (given by robot)	<NS, O0017>	
	and CNC not in Jog. mode (given by NC)	<NS, I0033>	
	and not part limit shutdown	<NS, AO0135>	
	and not system stop	<NS, AO0208>	
	and cart at station #2	<LS 21>	
	and robot not in motion	<NS, I0081>	
	and either after initial 4 parts loaded	<NS, AO0130>	
	OR after new system start (I0022) with AO0136 latched		
Note: (i.e. the system start <PB 2> was pressed again after the system stopped, having run 8 parts – or a multiple of 8 parts. through the system already).			

Table F.1 Sequences Description for PLC Control Program (Continued)

Part Inspection at station #2			
Seq. No.	Description	Sensor	Port
36	Take picture		O0050
	latch if system enabled	<SEE 5>	
	and cart at station 2	<LS 21>	
	and Robot gave signal	<NS, I0070>	
37	Compare part accept/reject masks with present and decide on output		
	ACCEPT	<NS>	O0192
	REJECT		O0193
Transfer Table #2			
Seq. No.	Description	Sensor	Port
38	The logic is essentially the same than the one explained for table 1. Thus, the logic will not be explained in detail at this point. For a detailed description refer to rung 96 – 114 Utilized switches (analog to transfer 1):		
		<LS 10A, 12A, 14A, 20A> <PC 11A>	
End of the program			
Seq. No.	Description	Sensor	Port
39	The first scan after "initial power on" was to establish constant and clearing conditions. At this point, then, the "power up" coil is finally energized, so that that actual process can start under predefined conditions.		O0480
	The controller jumps to step 1 for a new scan.		
End of Program			
Chamfering Operation			
Seq. No.	Description	Sensor	Port
**	Robot moves to position cart C		000000
	Only if system is enabled	<SEE5>	
	And machine tool is not in jog mode	<NS>	
	And cart at station 3	<LS 10>	
**	Execute the program of picking up the part and place it in the jig of Olivetti Machining Center		
**	Clamps are closed		0000000
	Only if the last line of execution program is performed	<*****>	
**	The chamfering program is executed		0000000
	Only if the part is there	<*****>	
	And the clamps are closed	<*****>	

Table F.1 Sequences Description for PLC Control Program (Continued)

	And the robot is at position out of chamfering working area	<*****>	
	Note: tool is changed according to the chamfering program, so once the program is scanned and there is a tool change, it send signal to the robot to grip the specified tool from 100 tool gripper and fix it in the Olivetti Machining center.		
**	Cart moves to the transporter		000000
	Only If the chamfering is done	<*****>	
	And the robot execution program of returning back the part to the cart is done	<*****>	

APPENDIX G

LADDER LOGIC DIAGRAM FOR NJIT FMS

The following figures show the ladder logic diagram used in GE series controller. The ports names consist of one or two letters followed by four digits as determined by manufacturer.

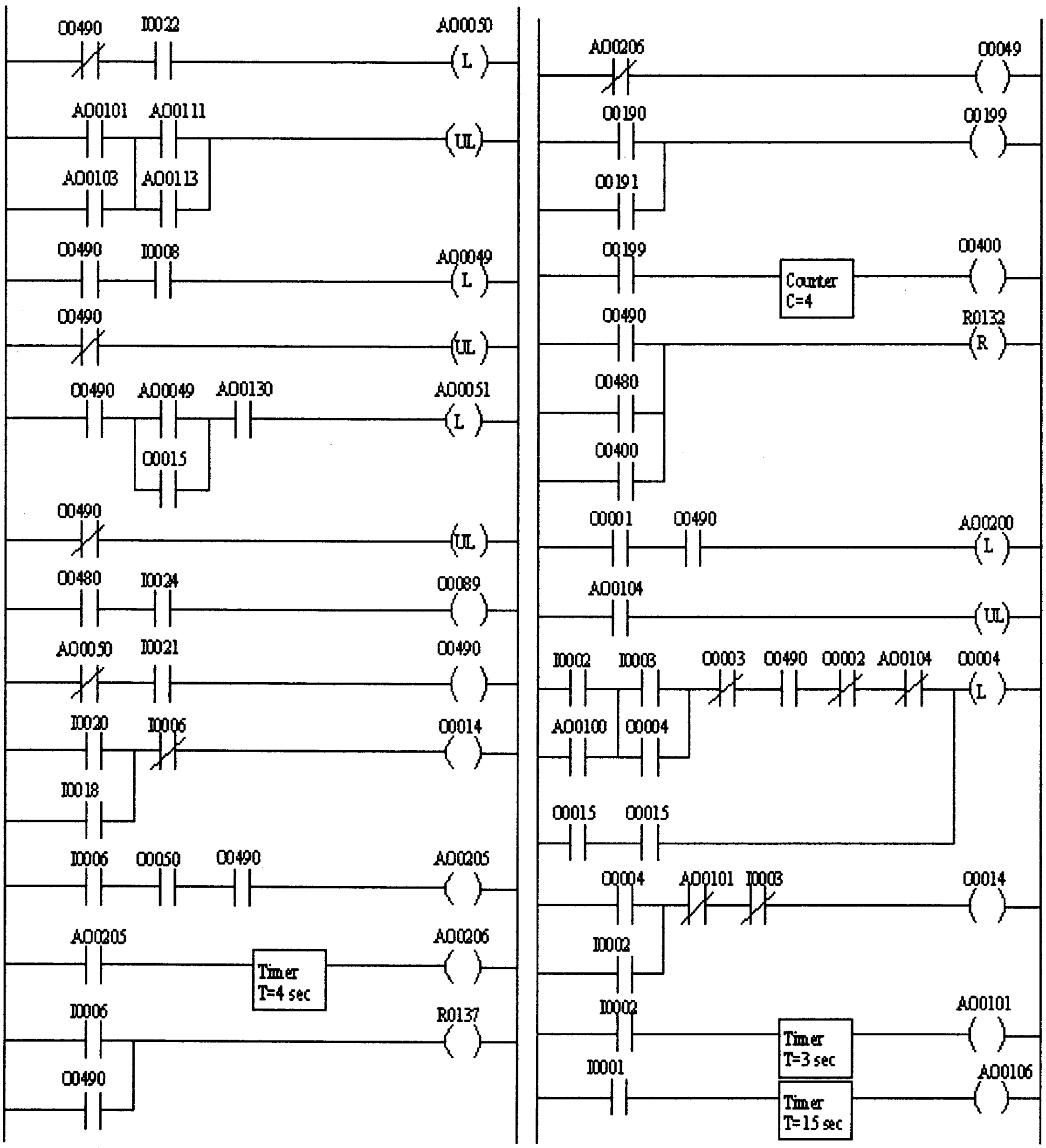


Figure G.1 LLD diagram used in NJIT FMS cell.

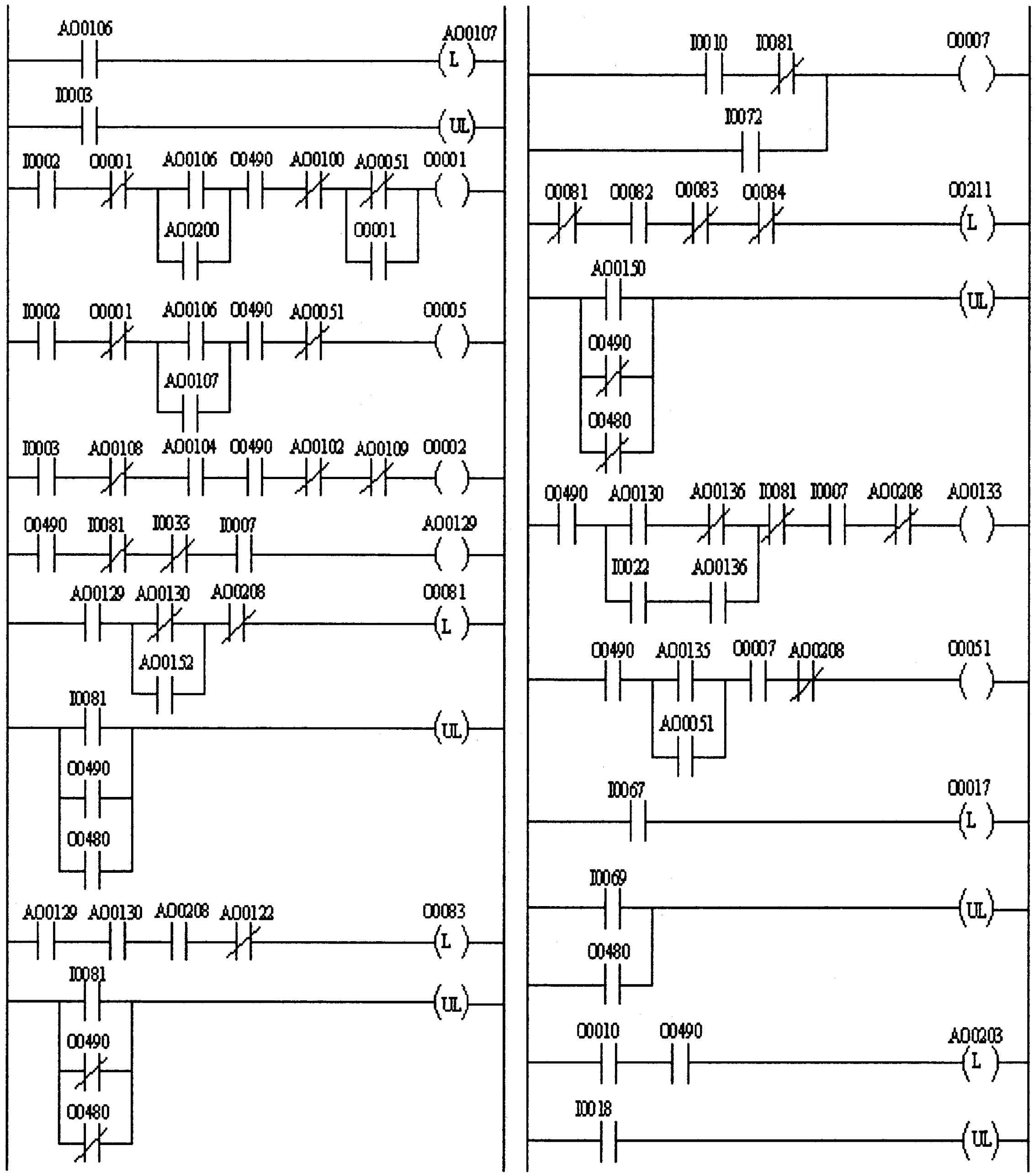


Figure G.1 LLD diagram used in NJIT FMS cell. (Continued)

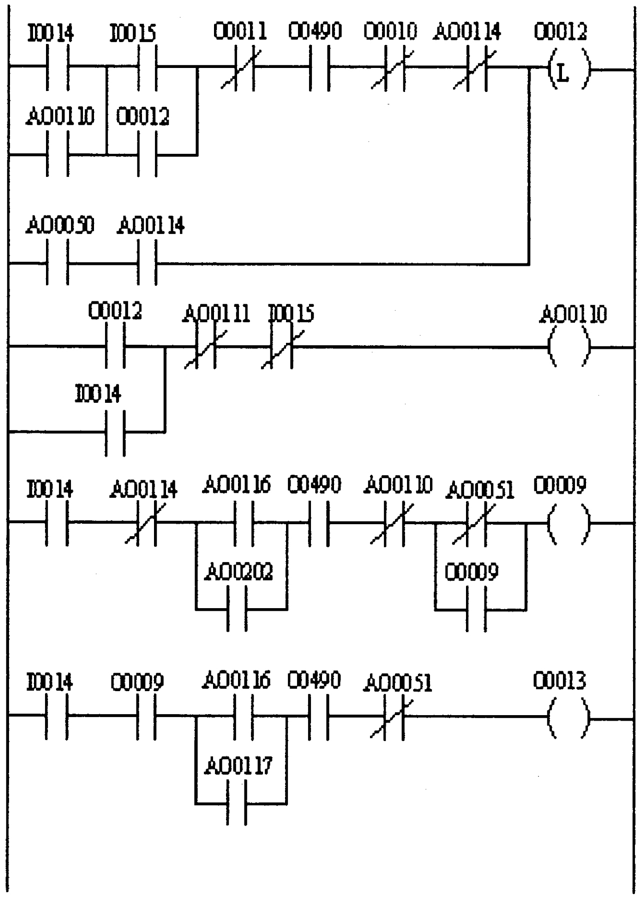


Figure G.1 LLD diagram used in NJIT FMS cell. (Continued)

APPENDIX H

PN PRESENTATION FOR LLD

The following table represents each sequence of the LLD shown in appendix F and the Petri net representation for that sequence.

Table H.1 Petri Net Presentations of the Sequences of LLD

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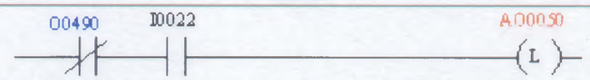
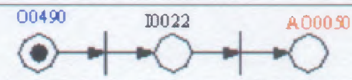
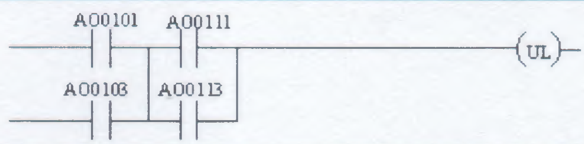
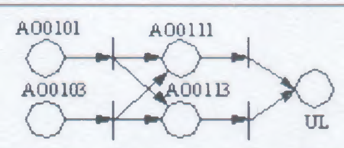
1		
2		
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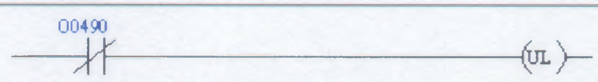
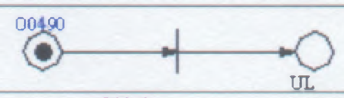
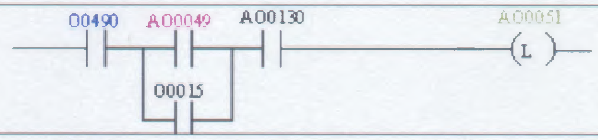
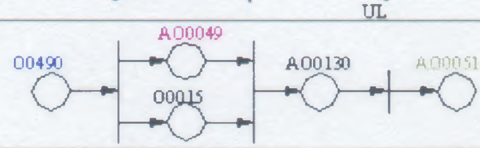
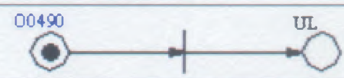
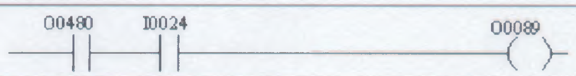
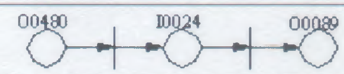
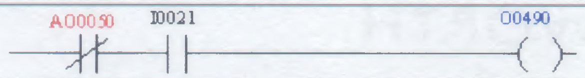
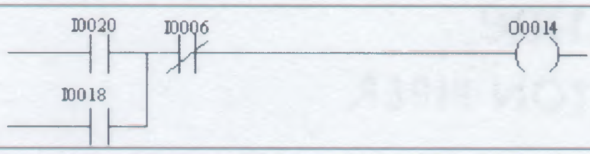
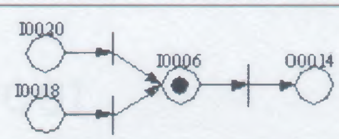
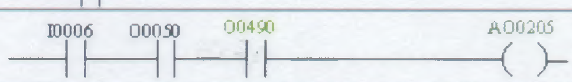
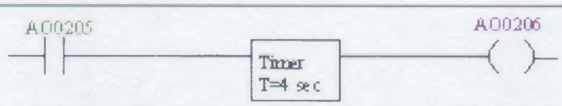
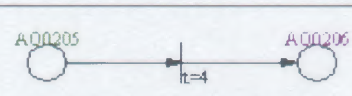
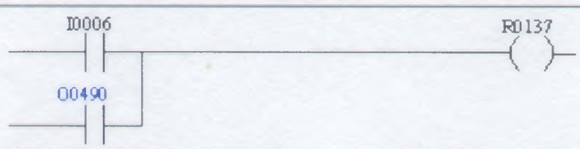
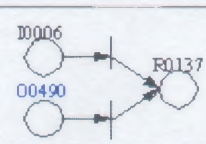
4		
5		
6		
7		
8		
9		
10		
11		
12		

Table H.1 Petri Net Presentations of the Sequences of LLD (Continued)

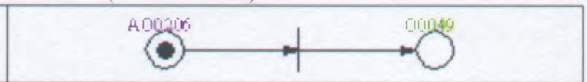
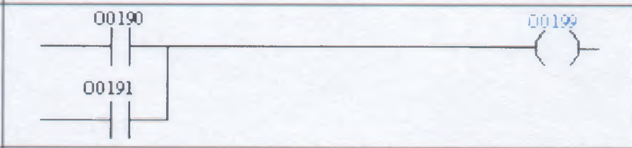
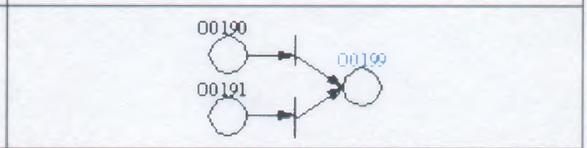
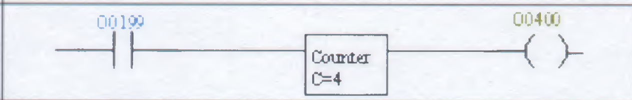
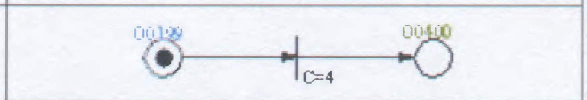
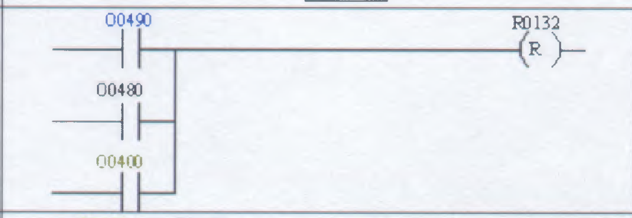
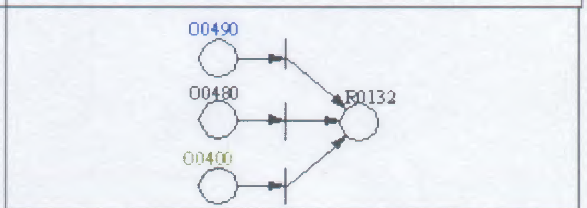
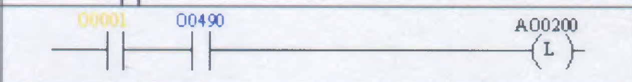
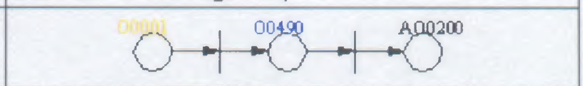
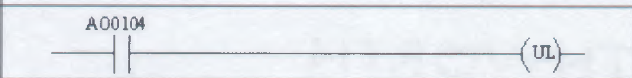
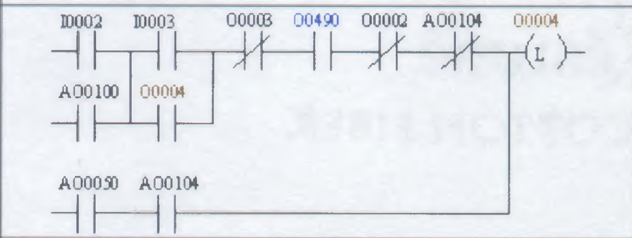
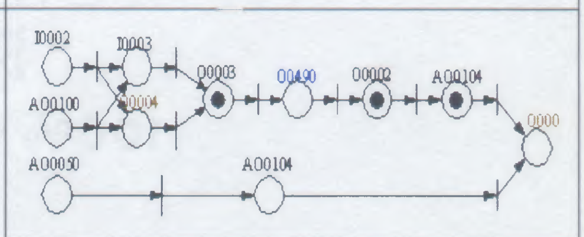
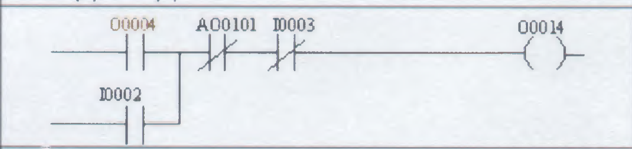
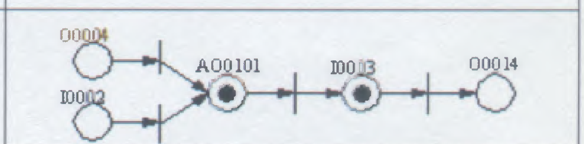
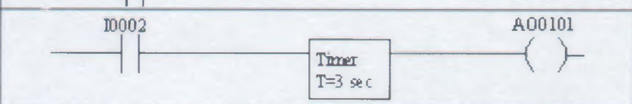
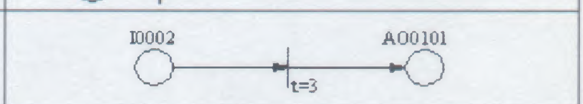
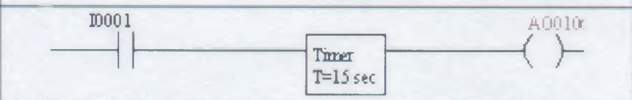
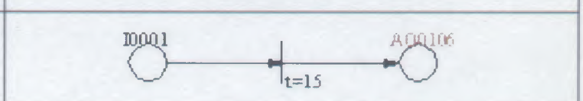
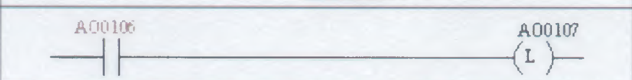
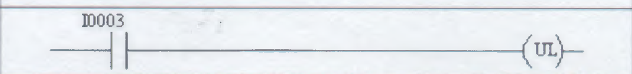
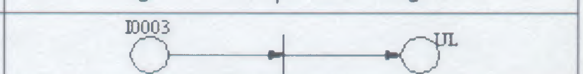
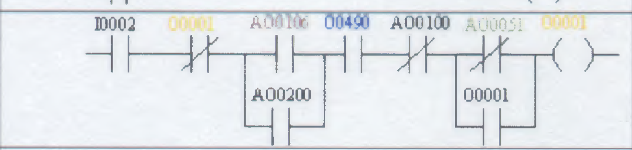
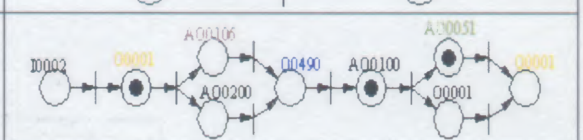
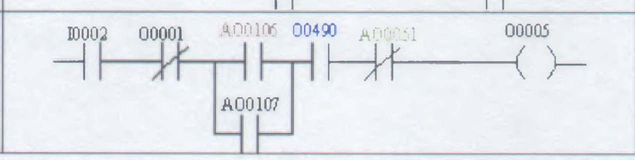
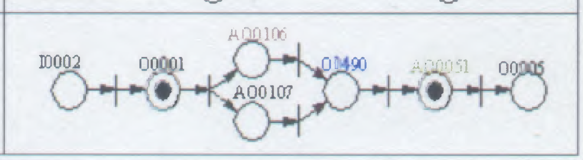
13		
14		
15		
16		
17		
18		
19		
20		
21		
22		
23		
24		
25		
26		

Table H.1 Petri Net Presentations of the Sequences of LLD (Continued)

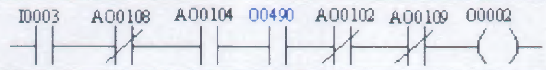
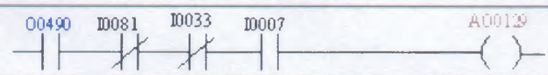
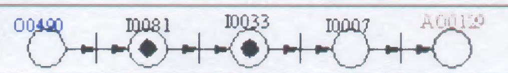
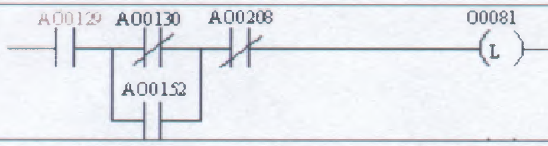
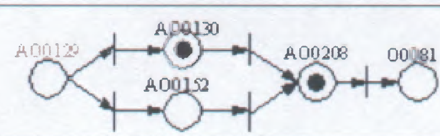
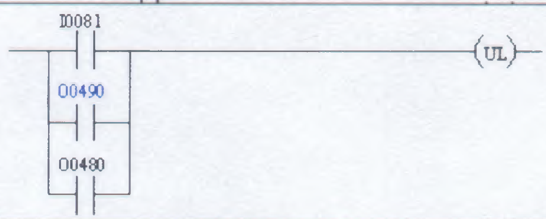
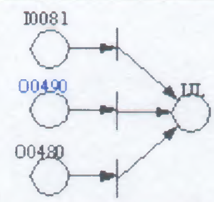
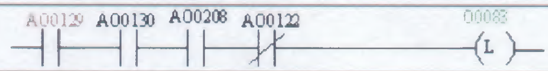
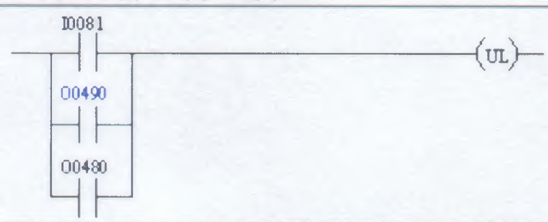
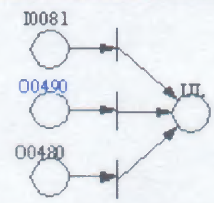
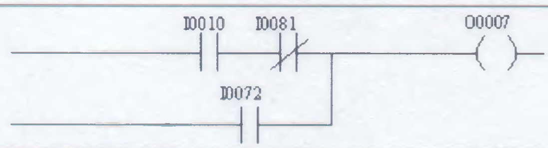
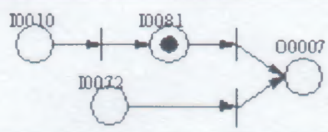
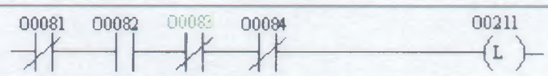
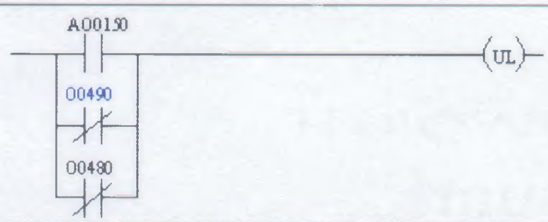
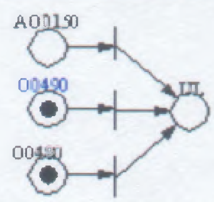
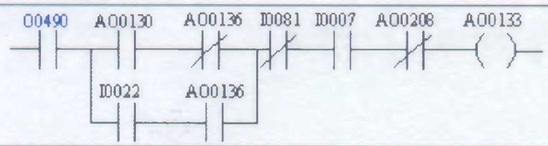
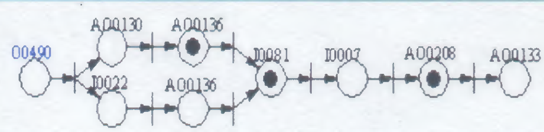
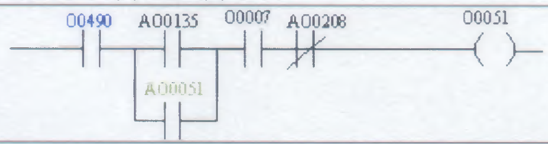
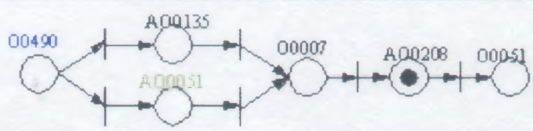
27		
28		
29		
30		
31		
32		
33		
34		
35		
36		
37		
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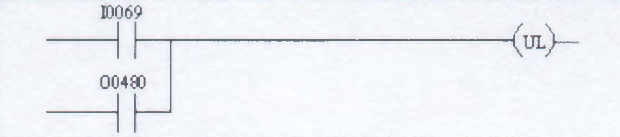
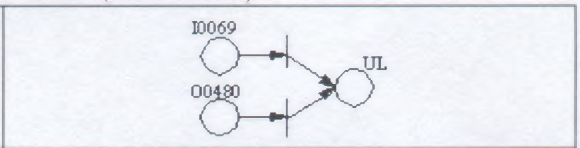
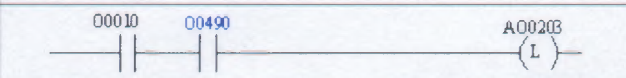
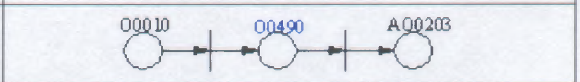
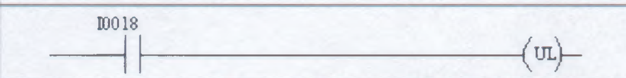
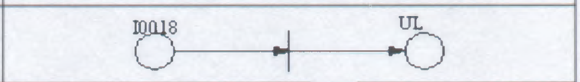
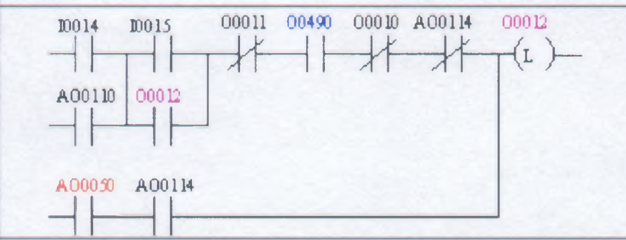
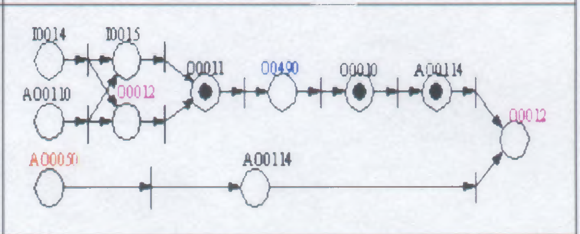
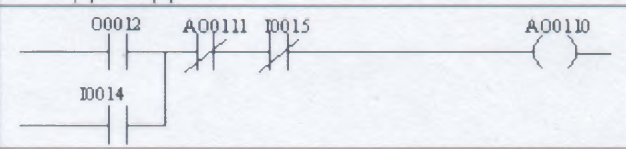
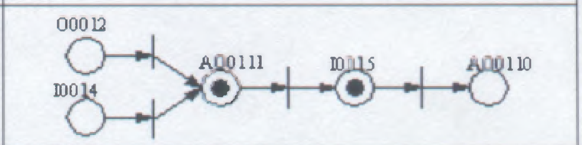
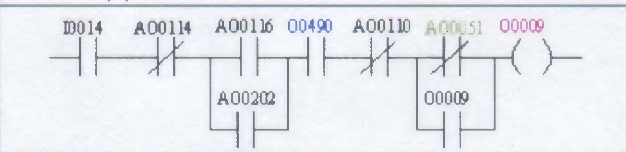
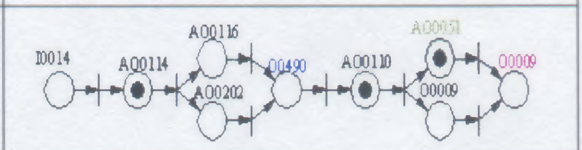
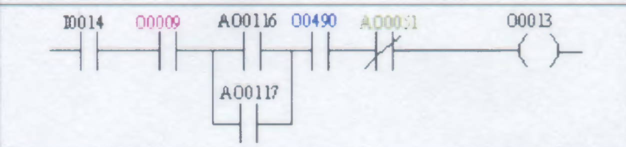
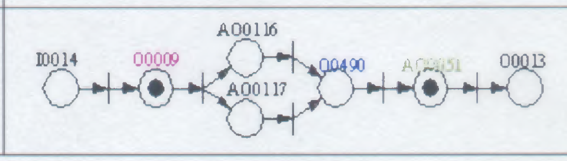
Table H.1 Petri Net Presentations of the Sequences of LLD (Continued)

39		
40		
41		
42		
43		
44		
45		

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