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A STUDY OF COMPUTER AIDED
MANUFACTURING

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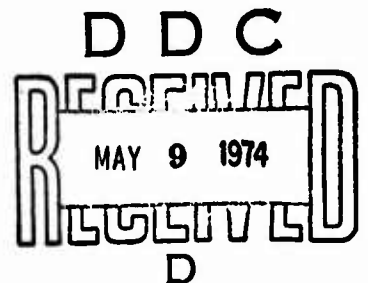
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1. INTRODUCTION

Computer aided manufacturing is an approach to automation. In manufacturing industries today, automation as conceived by such men as Evans, Jacquard, and many others has proven to be a powerful notion. The problems associated with manufacturing and processing by hand methods, such as quality, uniformity, and cost, can be readily tackled by automation.

What is automation? It is a contraction of the word automatic-operation. It is not synonymous with "mass production" which means volume manufacturing of interchangeable parts that Henry Ford did so successfully. Automation is more than "mechanization" which means to do things with mechanical tools, not necessarily automatically. Automation implicitly eliminates the undesirable characteristic of mechanization in which the operator functions as an integral part of the mechanical cycle, but relieves him to direct the machines. Whenever groups of processes are brought into a single continuous operation to create self-initiating and self-checking functions, automation is achieved.

1.1. The Meaning of Computer Aided Manufacturing

Computer aided manufacturing connotes a close interaction between man, the computer, and the machinery through the use of display terminals, special programming languages, and other means of interfacing. By using the light pen, keyboard, and other input devices, the man is able to communicate with the computer and receive response from it through the display. The computer translates the concepts, ideas, or engineering data given by the user into discrete manufacturing instructions. For example, an engineer

may generate a drawing of a mechanical part on the display terminal. As a result of previous programming, the computer "understands" the drawing, makes computations based on the stored knowledge of manufacturing processes, and responds with a cutting procedure in graphical form. The engineer may accept the result and issue a go-ahead, in which case, the cutting procedure generated is used to automatically drive the tooling machines. Or, he may wish to modify the cutting procedure, or even the original design.

1.2. Historical Background

It is interesting to look back and review the early ideas with our present knowledge. In 1956, George R. Price published in Fortune Magazine an article about a future system that integrates the concepts of computer aided design and computer aided production into one [PRICE]. The idea was to allow engineering data be transformed into physical hardware directly. The future system consists of a computer, graphics terminals, and numerical control machines. The computer is used to convert conceptual information into engineering data and to do graphical information processing. The graphics terminals allow an engineer to add, or delete from his displayed design, or to rotate the image for the study of the various surfaces. A multi-axis Numerical Control machine is driven by the computer to produce mechanical parts.

A closer look at Price's design machine reveals most of the feature available in the present-day graphics terminals. A keyboard is available to specify basic surface designs. It has five groups of keys. The first group are operation keys, such as: Construct, Portray, Modify, Superpose,

and Store. The second group are category keys which inform the computer what type of data is coming in. They are: Model, Part, Surface, Shape, and Location. The third group are the basic geometric element keys such as: Plane, Cylinder, Cone, Quadratic Surface, and Surface of Revolution. The fourth group are graphical symbol manipulation keys. They are: Parallel, Perpendicular, Intersect, and Concentric. The last group are locational keys. They are: Origin, X-axis, Y-axis, Z-axis, and XY-plane. Present day equivalent of a joystick (called a "locator") and a tracker-ball (called a "rotator") are also available to manipulate the displayed image of a design.

For an overall design of a mechanical part, the keyboard is used. To construct a cylindrical object, an engineer could press the following keys:

Construct : Surfacel
 Shape : Plane
 Location : Perpendicular
 Z-axis : 2.3"
 Intersect : Surface2

Construct : Surface2
 Shape : Cylinder

. .
 . .
 . .

Construct : Surface3

Shape : Plane

. .
. .
. .

When this description is complete, the computer derives the equation of various surfaces, computes the intersections, and stores the information in memory.

Detail modifications of the design can be performed with the joystick and the tracker-ball. A three dimensional shaded image is displayed by pressing the Portray key. The joystick is used as a positioning device for a cursor, Arrow. To drill a slanted hole on Surface2 in the cylinder previously constructed, one could use the joystick to point the arrow at a desired angle, and type:

Construct : Surface4

Shape : Cylinder

Radius : 0.125

Location : Arrow

Intersect : Surface2

The tracker-ball can be used to rotate parts of the entire image of the design. A special hardware called the Scaler is used to reduce or enlarge parts of the design referred to by its surface designation.

After the entire design process is over, the information stored in the computer is converted into a form suitable for Numerical Control machines. An experimental prototype of the design can be made on site. Equipments are also available to output Numerical Control tapes for larger scale production.

This dream machine of Price had incorporated so many good ideas that we are actually witnessing aspects of his design realized. It is well-known that our present day computer graphics techniques applies to most, if not all, of the computer aided design features suggested by Price [Newman and Sproull]. It is equally true that Numerical Control programming techniques has evolved to a state beyond that envisioned by Price surfaces such as the modeling of sculpture surfaces [IITRI]. What seems to be able to yield an integrated system that fully automates the entire manufacturing process is a system that automatically converts engineering ideas and design data into manufacturing instructions. This system can be viewed as a bridge that links the two highly developed technologies, Computer Graphics and Numerical Control. Indeed, this is a problem confronted and tackled by some leading manufacturing industries. There are two approaches currently taken, and they are dealt with in detail in the following chapters.

2. PROCESS PLANNING

Process Planning is concerned with translating engineering specifications into manufacturing specifications. The heart of a Process Planning system is a model including optimization functions and constraints. A model of a metal cutting process would be a sequence of various cuts and the workstations involved. Optimization functions are formulated to minimize the production time and to schedule the work stations. Some of the typical constraints for metal cutting are: cutter tolerance and surface finish. The basic approach is that there exists a family structure of parts, e.g. parts can be grouped according to similarity in manufacturing process, or similarity in geometric configurations.

Basically, a Process Planning system involves two phases of operations: A manual classification phase and an automatic parameter computation (and sometimes, optimization) phase. A planner examines the mechanical drawings of a part to be manufactured, identifies the necessary operations including routing through different work stations, retrieves the family of parts that has similar operations done before, compares and tabulates the variations of the part and the family. The table is then used as input to a program that computes such parameters as feed and speed.

The basic idea of having parts families is a very practical idea. It readily provides a structure of machine operations once the new part is identified as belonging to a certain family. Below are two case studies of Process Planning systems.

2.1. The IBM Automated Manufacturing Planning System

IBM has a system that analyses a manufacturing process in a systematic way. The result of the analysis is coded on a special form which is translated into FORTRAN programs [IBM1]. A manufacturing process is analyzed by its input (e.g. blueprints) and output (i.e. routing, operations, and time standards). The basis of analysis is Decision Logic [IBM2]. The result of the analysis is tabulated, flowcharted, and coded in FORTRAN-like statements. A program called the IBM 1401 Decision Logic Translator [IBM3] accepts these codes and produces FORTRAN source programs.

2.1.1. Input Analysis

An input specification analysis is conducted first to provide a structure for system inputs. The purpose is to identify sets of characteristics for a part and the membership in a family. The test can be part name, similarity of process, or product grouping. The characteristics of the part are tabulated by selecting one part out of the family (e.g. the largest one) and comparing, rather than generalizing all the parts in the family. The characteristics are then each given a range of values according to the blueprint, and mnemonics are assigned. An example of the characteristic table of a spur gear would be:

Number of teeth	N	6--10
Material	M	C1020,3140, brass
Outside diameter	OD	3--5"
Pitch diameter	PD	2.5--4.5"
Base diameter	BD	1.75--3.75"
Inside diameter	ID	0.5"
Overall diameter	OW	0.375--0.500"
Tooth width	TW	0.720--0.740"
Pressure angle	PA	22.5
Corner radius	CR	0.125"
Keyway	KW	0.125" x 0.125"

2.1.2. Output Analysis

Output is next structured in three steps: routing, operation methods, and time standards. The purpose of routing analysis is to determine what sequence of operation is necessary to manufacture the part. The logic for such analysis is based on Decision Tables [IBM2]. An example of the decision logic would be as follows. If the part name is "Gear Hub" the first operation is always "Drill". If the part name is "Shaft" the first operation is always "Saw". Successive operation are established by examining other characteristics of the part; such as: "Does the hub have a special notch?" A routing sequence is thus established and flowcharted.

Operation method analysis is next performed. Its purpose is to describe the precise methods of instructing machine operators in the

production of the part. It covers the capabilities of four types of work center resources: (1) machines, (2) tools, jigs, and fixtures, (3) raw materials, and (4) operation descriptions. The capabilities of the machines and fixtures are looked up so that the routing established earlier can be assigned with work station numbers. The handling of raw material is much like tools and fixtures. The characteristics of the raw material must conform with the classifications of the machines. Operator descriptions are those for the machine operator, but not associated with elements of machine capabilities such as "adjust rpm". They are a variety of manual operations, such as: clip leads, take reading, etc. Lastly, time standards are looked up and fed into formulas for time standard calculations.

2.1.3. Programming Considerations

The result of the input and output analysis is coded on a special Decision Logic Coding Form. The code is FORTRAN-like. The form is composed of special columns and is designed to ease the task of programming. If the variable x in the if statement, in the following illustration, is greater than 1.35, the subroutine named 17 would be called in the following do statement because of the correspondence of 1.35 and 17 in column position.

```

if x GE   .38   .80   1.35   2.70   4.20   7.10

do Table  12   17   21    4    19    3

```

This special kind of program statement can be translated into FORTRAN source programs by using the IBM 1401 Decision Logic Translator. Consequently, a manufacturing process is computerized.

2.2. Computer Algorithms for Process Planning

Berra and Barash [BERRA] reports an algorithm for generating and optimizing a set of machine tooling parameters for the part family of turned shafts and spindles. The basic idea of the algorithm is as follows. A turned shaft may have many sections of different and varying diameters. For example, a shaft may have sections that are right circular cylinders, tapers, circular arcs, or shoulders. The authors consider the interfaces of these types of surfaces to be of great importance, and limit the number of possible interfaces to 8. A counter is set up in the program to indicate the current section of the shaft and it is incremented when an interface is encountered. A decision is made at this point to determine what type of surface the next section is. For example, is it an expanding taper following this right circular cylinder, or is it a contracting taper? Appropriate subroutine is called which computes the length of cut, the finishing diameter, finishing coordinates for the next section. The program terminates when the entire length of the work has been covered and other parameters such as feed and speed optimized.

The algorithm is a five stage process. The input to the algorithm is a matrix called Component Data Matrix. It is prepared in advance and is a numerical representation of the finished component. It contains such information as number and type of surface, lengths, diameters, tolerances, and surface finish designations. Utilizing this input data, a Machine Requirement Matrix is generated. This matrix contains information on what machining operations are required for each surface on the shaft. The second stage involves generating four other matrices. These matrices are numerical

representations of the component at various stages of the manufacturing process. They are rough cut, rough grinding, finish turning, and finish grinding. The third stage involves the selection of raw material size, a machine and the tooling needed based on their stored characteristics. The fourth stage involves planning and optimization. Such parameters as feed, speed, cutting force, and machine horsepower required are computed and optimized. The general method of optimization is to take the longest possible cut first followed by the the next longest. If the horsepower required for the cutting operation exceeds the horsepower available, the feed is reduced by a small amount and the program loops the fourth stage until the horsepower constraint is satisfied. The last stage involves the calculation of the cost, time, and other data.

Scott reports on a method of automated planning for manufacturing which is called "Regenerative Shop Planning"[SCOTT]. The logic by which the original component was manufactured is placed in computer storage and used in the planning of subsequent components. Methods of selecting part families include an examination of the relationships that exist between the operations performed within a particular process area and the resultant characteristics of the produced part, and relationships based on similarities between geometry and configuration.

3. NUMERICAL CONTROL

There are few engineering technology that have created as keen an interest and have forced so many changes in the industries as Numerical Control. The technology of Numerical Control encompasses almost every aspect of the manufacturing industries. It is used in metal work, adhesive bonding, painting, assembly operations on electronic equipments, and many others.

Numerical Control as a means of automation is to be distinguished from "fixed automation" which is sometimes called "Detroit automation". Fixed automation utilizes mechanical cams to sequence a variety of tooling machines in such a way that there can be no variations. The task of resetting such a cam-driven tooling machine is a difficult one. It requires days to set up; for more complex machines such as those in the Automotive industry, it requires many weeks.

Numerical Control offers the flexibility that fixed automation does not have. It makes possible the economical use of tooling machines even for a small number of parts. If modifications are necessary, the process is relatively simple.

One of the major application areas of Numerical Control is in the parts manufacturing industries. Computer control is done by digitizing the axial and radial movements of the tool or the worktable. There are many different kinds of cutting operations performed by tooling machines, such as: drilling, milling, boring, turning, tapping, reaming, facing, and many others. Basically, these operations can be grouped into two categories. Since the cutter (or the workpiece) moves either circularly or linearly, the

process of cutting results either a flat surface of a cylindrical surface. Complex sculptured surfaces are cut by "patching" smaller pieces of simpler surfaces together.

In conjunction with the intrinsic capabilities of hole making and surface smoothing, Numerical Control equipments can be operated in two modes, the Positioning (point-to-point) mode, or the Contouring (continuous path) mode. A Positioning Numerical Control system is initially designed for moving the cutter or the worktable and perform operations such as drilling, boring, inserting a component, ... etc. It operates in an absolute coordinate system. A Contouring Numerical Control system is suitable for milling and facing. It operates on relative incremental positioning from the previous location of the cutter.

There are many technical problem areas associated with Numerical Control as a computer system, such as the development of programming languages, more efficient means of Input/Output, Numerical Control machine networks, and so on. There is one area which is considered to have significant contribution to the state of the art of Numerical Control technology. It is the utilization of interactive graphics as a more powerful means of programming.

The basic idea in Graphics Numerical Control is that of representing the cutter tool path in graphical form as is done instead of the alphanumeric form in conventional programming. The programmer, rather than writing programs, uses a lightpen to enter the desired cutter path on a graphics terminal that displays an image of the part. This technique is reported to

have achieved a saving which is only one-eighth the cost for manual programming at McDonnell-Douglas [CARLSON]. In Japan, a factor of six is achieved in the reduction of programming time [YAMAGUCHI].

3.1. Interactive Computer Graphics Techniques

It is important to understand how the lightpen is used for the computer to "see" a displayed item, or is used as a drawing device. When the computer "sees" a part of the display, the lightpen is used as a "pointing" device. When the lightpen is used to draw lines on a display screen, we say it is a "positioning" device.

3.1.1. The Lightpen

The lightpen has two elements, a photocell and an amplifier. It is connected by cable or fiber-optic to a flip-flop. The flip-flop can be read or cleared by the computer. When the lightpen is held at the screen and a switch depressed, an displayed item on the screen that lies within the field of view of the lightpen intensifies the photocell and sets the flip-flop. This interrupts the computer, halts the display momentarily, and requests that the contents of certain display registers be read. Since the content of those registers at the instant the display halts must be the x-y coordinates of the point where the display plotting stops, the computer is thus able to "see" the position of a point on the display screen. This is the pointing function of the lightpen.

Positioning with the lightpen is a more complex process. It involves not only pointing at a display symbol, (normally a tracking cross which is a small plus sign composed of many dots along the axes), but also

moving the symbol to a new location. This amounts to dragging the tracking cross and can be done as follows. The dots composing the tracking cross are weighted differently; the center has the highest weight and the end points has the lowest weight, for example. When the tracking cross is being pointed at, the computer identifies, by the programmed interrupt scheme mentioned previously, only the dots that lie within the field of view of the lightpen. The "center of gravity" of the portion detected is computed and is used as the center of the tracking cross when the display resumes. (This halting and resuming of display happens in such a short duration that the eye is unable to notice.) By iterating this process, one can "move" the tracking cross to anywhere on the screen.

3.1.2. Manipulating Displayed Objects

When the display image contains a number of figures, it is often necessary to select a single one for calculation or manipulation. One method of singling out a figure is to position the tracking cross on or near any line of the figure. The position of the tracking cross is used as the reference for calculating the distance between the center of the cross and each of the edges of all the figures of the screen. If the distance between the cross and one edge is found to be within tolerance, the figure to which the edge belongs is the one selected.

After a figure is selected, one may wish to draw a path on that figure. This is done in Graphics Numerical Control programming to program a cutter path for a part. The cutter path programmed is a two-dimensional, with the third dimension as a variable of the input from the keyboard.

There are two ways to do this, the point-to-point method, and the contouring method, both requiring the technique of positioning the tracking cross.

With the point-to-point method, the tracking cross is moved from one location to another location on the screen forming a straight line. The line can be represented in linear parametric form:

$$x = (1 - A) \times x_1 + A \times x_2$$

$$y = (1 - A) \times y_1 + A \times y_2$$

where (x_1, y_1) and (x_2, y_2) are the two end points of the line. Ranging the value of A from 0 to 1 will trace out the entire line. A sequence of such point-to-point operations will result a cutter path.

The contouring method requires more computation since the cutter path is supposed to follow a given contour precisely. This is done in a similar manner to the selection of a figure. When the tracking cross is moved along a line segment of a figure, the distance between the path traced and all the line segments are computed. If the distance is within tolerance, a path is computed that is parallel to the line closest to the trace. This parallel line corrects any irregularity that may be introduced by hand.

3.2. Case Studies

3.2.1. Lockheed Aircraft Company

Lockheed-Georgia [LOCKHEED] developed a system for interfacing Computer Graphics and Numerical Control. It is believed to be the first production system in the Aircraft industry. In addition to having on-line

drafting capabilities, the system can perform graphical programming tasks. The system operates in two modes; the point-to-point mode and the profiling mode. In the point-to-point mode, the programmer causes the cutter to move in a straight line to a new location indicated by the tracking cross on a display terminal. By repeating this positioning operation, an arbitrary surface can be swathed. To use the profiling mode, the programmer indicates the desired profile with the tracking cross, the cutter then jumps from an earlier position to a new position that is tangent to the indicated profile, and starts in a clockwise or counter-clockwise cutting direction.

When the programmer has completed the part, the data for tool path are output on tape and post-processed to add special control features required for the particular type of machine tool to be used (e.g. 3-axis, 4-axis, or 5-axis milling machine). This system was used to program about 50 parts and 300 templates for the C-5A aircraft.

3.2.2. Japan

In Japan, a similar system is constructed [YAMAGUCHI]. It offers two additional features compared to the Lockheed system. (1) The system can be implemented on a small computer having 16 Kiloword core (16 bits/word). (2) Basic geometric shapes such as a sphere, of a cylindrical groove, are cut automatically.

In addition to having the point-to-point and contouring modes, the system offers a repetitive mode. When the repetitive mode is in use, the programmer has to move the cutter to a proper location in advance (for defining the set point) and has to give the system some information about the shape

of the cut. The basic shapes are: Plain, Slope, Cylindrical Groove, Tetrahedron, Sphere, and Curve Fitting. The cutting simulation is then carried out at a constant z value, and this cycle is repeated by changing Δz . To cut a cylindrical groove, for example, the programmer indicates the four line segments composing the contour in a sequence on the display with a lightpen. He then types in such information as the radius of cross section, the upper and lower surface heights, and the scallop height of the machine surface. The system will repeat cutting motions automatically. A feed-rate light button is also available as well as a rotation button which controls the climb of the cutter on a circular drive surface.

3.2.3. McDonnell Aircraft Company

McDonnell-Douglas has a more advanced system than any other in the industry [McDONNELL1, McDONNELL2]. The input to the system is a mathematical description of the part instead of a cutter path as in other systems. The programmer, using a lightpen, indicates all the line segments that compose the part successively. The system then derives mathematical description for the part such as the (x,y,z) coordinates for the vertices, surface types, ...etc, and stores this data in computer. After the programmer has finished supplying the information necessary to cut the part, including the set-point, the diameter of the cutter, the spindle speed, the check and drive surface, etc., APT source statements are created and are subject to inspection by the programmer. To use these statements generated, the programmer can add other control statements so as to combine them into an executable program. Upon visual inspection of the cutting simulation, the part can be

made. The part is then subject to quality assurance test. By holding the lightpen over the surface of the image of the part, the programmer can generate points where an inspection machine is to probe. The points are translated into apt statements to guide the probe. It is reported that a fully automated version of this process is under development[BERADINO].

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