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COMPONENT DESIGN AND MANUFACTURE USING COMPUTERS - THE PRESENT POSITION [1]

by

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The United Nations and BUMAR have organised this meeting in order that experience in the use of computers and computer peripherals in an industrial environment can be discussed between people from the industrialised and the developing countries. The objective is to expose aspects or areas of computer technology in order that their usefullness in individual situations can be more effectively assessed. The purpose of the paper is to set out what is readily available at present in three areas encountered in design and manufacture in industry. These are

1) the analytual
2) the graphical

and 3) the numerically controlled manufacturing areas

The computers themselves and their various peripheral devices work at the binary digit level. They can compare trains of binary pulses and from the result pursue a particular sequence of events - a decession process. They can perform arithmetic operations on the pulse trains and they can control the movement of stepper motors, switches, etc. using them. These and the prodegous speed of operation are the basic ingredients we need in order to transfer our wishes into controlled automatic processes.

Between this computer control level and the human operator or user there have evolved a number of languages and translaters (compilers). These enable the user to instruct the computer in a mode more akin to his existing and every day manual processes. Many of these languages (Fortran, Algol Gino, APT, machine language) are now widely used and understood

understood. In the nature of all developing technologies each of these languages have evolved to satisfy particular needs. Now, however, we see signs of integrated languages (and compilers) being constructed to allow combinations of graphics and manufacture, for example, to be considered as one entity. We will return to this aspect later.

Since such convenient languages are readily available our task is to examine how they might be used to assist us in setting out our wishes and how because of the computer new techniques and approaches are available to us.

Analytical Technique

All computer techniques are essentially analytical but the term is used here to identify the area of design where in the past manual or slide rule calculations were involved. This is probably the area in which most development has taken place and an attempt will be made here to present a summary

1. A one- to-one translation of Algebraic design routines. This probably requires the lowest level of ingenuity and skill requiring only a knowledge of the language - FORTRAN, ALGOL etc - and an understanding of the pencil and paper procedure. Many international standards and codes of practice are being redrafted to aid computer usage. These usually involve line by line translation as in

$$L = \frac{1}{2}\sqrt{d_A^2 - d_B^2} + \frac{1}{2}\sqrt{D_A^2 - D_B^2} - C \sin\alpha$$

which may become

```
SLEN = 0.5*SQRT (DA*DA -DB*DB) + 0.5*SQRT (DAA*DAA -DBB*DBB) -
          C*SIN(ALFA)
```

or by substituting a routine or a group of instructions as in

$$A = \int bdx$$

which may become

```
      AREA = 0.0
      DO 20 I = 1,N
      DX = X(I + 1) - X(I)
      B = (Y(I + 1) + Y(I))*0.5
20    AREA = B*DX + AREA
```

2) Handling tabular and graphical data.

Many of the codes of practice incorporate tabular data such as properties of material, available dimension or cross-sectional information etc. where searches have to be made in order to effect a final solution. The simplest way to do this is by a linear search. The values are stored in a vector (or matrix) and the value to be identified is compared with each one stored in turn till a match is found.

```
      DO 10 I = 1,N
      IF (NVAL.EQ.NUM(I)) GO TO 20
10    CONTINUE
15    ----------
20    ----------
```

If control passes to statement 20 the I will contain the index of the matching value. If statement 15 is reached no match has been found. This required an average of N/2 searches and for large vectors (or matrices) this is not very efficient.

This can be improved by using a Binary search. The method requires an ordered table of values. A given value is compared with an item in the middle of the table to determine whether the top or bottom halves should be searched further. The value is then compared with the central value in the appropriate half, and so on till a match is obtained. The number of comparisons needed will be $\log_2 N$.

e.g. Say 60 value table - add three very large numbers N2 = 32

```
         I = 0
         IAV = N2
10       IS = I + IAV
         IF (VAL.GT.TABVAL (IS))  I = IS
         IAV = IAV/2
         IF (IAV.GT.0) GO TO 10
```

where N2 is a power of 2 and the number of TABVAL^{s} is accommodated by 2 x N2.

Where the data is originally in the form of a sparsely filled matrix it is usually more convenient to store the non-zero values only and to use a similar matrix to store the address. Once a search is made to locate the value its actual position can be obtained from the similar location in the address matrix.

Graphical data is widely used in codes of practise. Sometimes the graphs can be reduced to mathematical equations and can be handled easily by the computer. Most frequently however the graphs represent experimental data where piece wise curve fitting would only be possible. In such cases it is possible (fig. 1) to digitise the curves to form a matrix of values and use an interpolation technique.

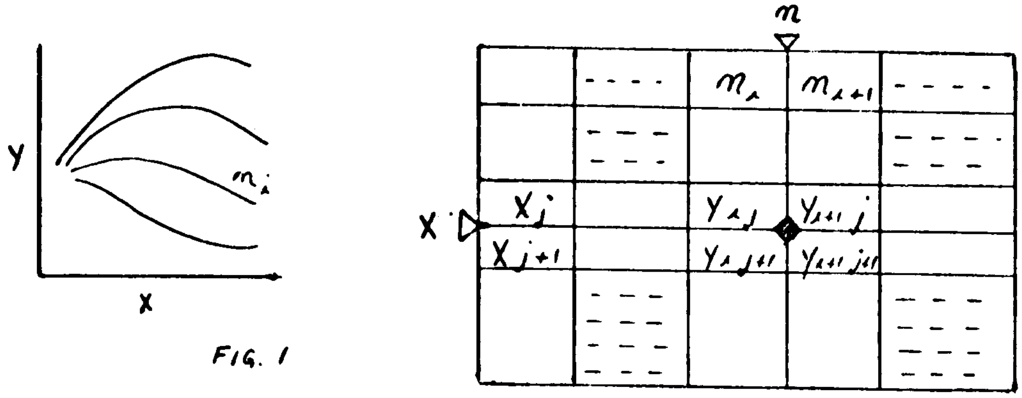


FIG. 1

to determine Y from X and n. i.e. ◆

Alternatively, with the aid of a graphics terminal, an interactive solution could be achieved by a process simulating the manual method used in the original code. By digitising the graphs, they can be presented on the graphics screen and annotated. The cross-wire cursor can then be positioned on the screened graph. The physical position of the cursor can then be related to the actual X,Y value by interogating two vectors which are composed of the incremental values on the axes of the graph.

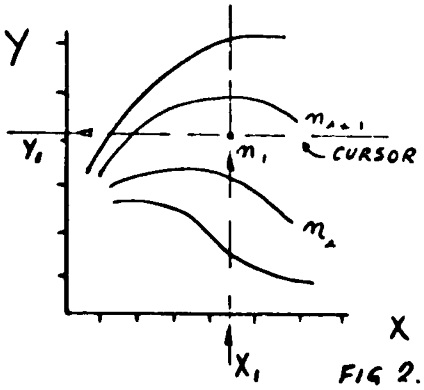


FIG 2.

3) Using Principle from code of Practise but redrafting method to suit computer.

Most of the codes of practise have been established to suit the human computer i.e. with visual selection and pre-calculated data displayed in tabular or graphical form. Since the computer characteristic is vastly different from that of the human the general organisation of the solution can be quite different. By way of illustration and to contrast it with the graphical data of the previous section consider the British code of practise for gear design.

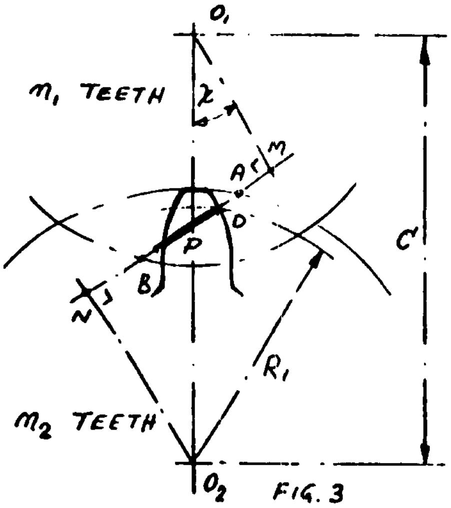


FIG. 3

The criteria for the strength of the teeth in this code is the tooth loading at one extreme of the single contact zone. This position of course depends on the combination of wheels with n_1 and n_2 teeth and can be determined from the geometry fig. 3

$$ND = C \sin\gamma - \sqrt{O_1B^2 - O_1M^2} + p \cos$$

$$R_1 = \sqrt{ND^2 + O_2N^2}$$

Using a simulation of the gear cutting process fig. 4 one can determine the shape of the tooth generated from a basic rack. The proportions of the rack can be arranged to coincide with the actual cutter tool which would be used in the manufacturing process.

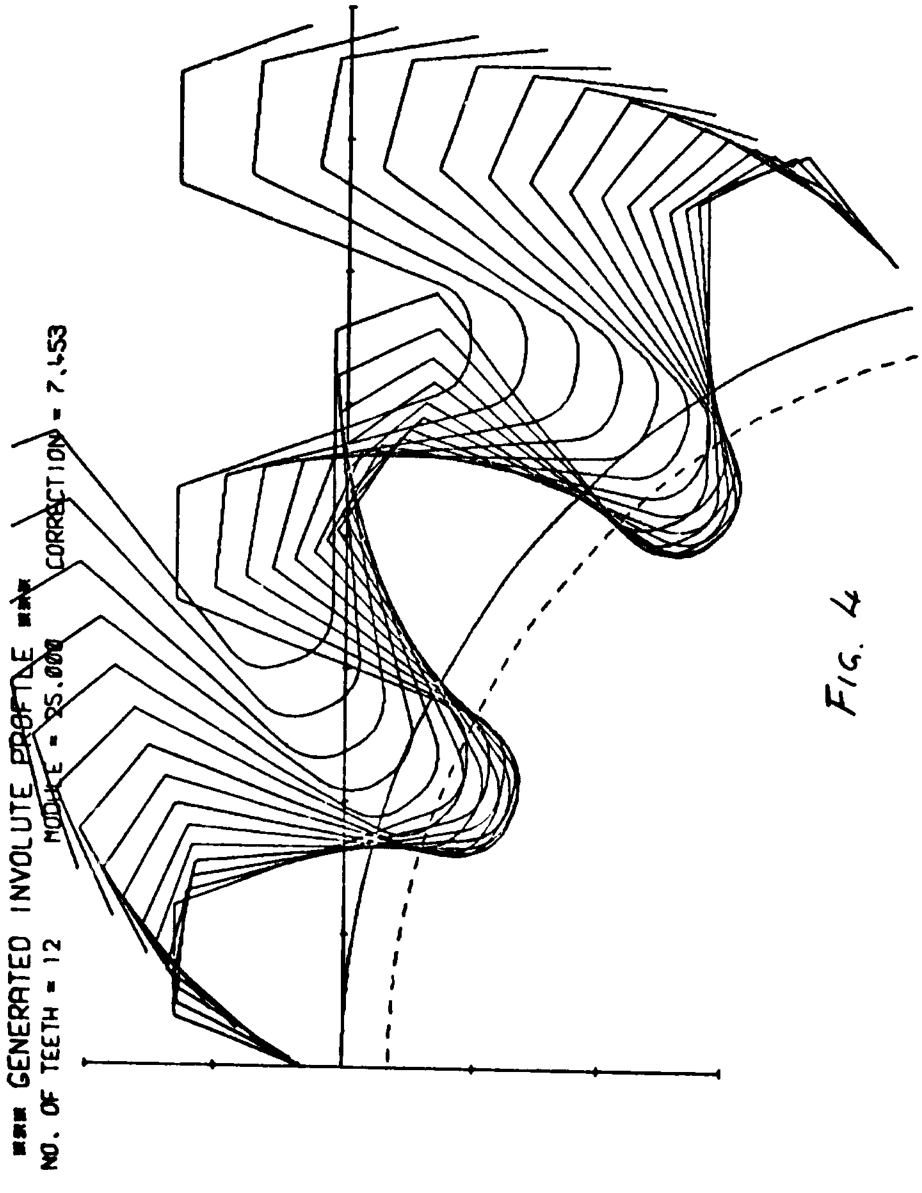

*** GENERATED INVOLUTE PROFILE ***
NO. OF TEETH = 12
MODULE = 25.000
CORRECTION = 7.453

FIG. 4

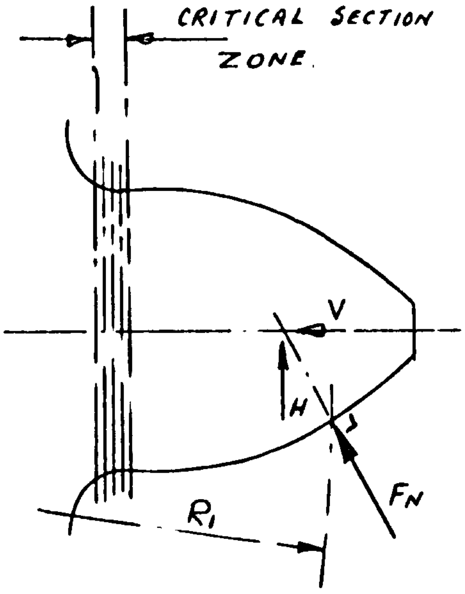


FIG 5

Knowing the profile data and the radius R_1 at which the tooth force FN is applied normal to the surface, the components V & H can be determined on the centre line of the tooth fig. 5 . The stresses produced by these components at a section towards the root of the tooth can be readily obtained. Using an iterative procedure involving the location of this section - over a narrow band - the appropriate maximum stress condition can be established. The lesson to be learned from this in connection with the integration of codes of practise in a C.A.D. system is that the direct conversion of manual techniques, while it is the obvious course, is not necessaril the simplest or most flexible or the least bulky in terms of computer space. Some tricky data bank problems can be avoided by reverting to basic principles and rephrasing the problem to suit the new medium.

5) New Analytical techniques for the computer

Because of the very fast speed of computation which is possible with computers approximate analytical methods involving iterative techniques and vast numbers of calculation can be accomplished in relatively short spaces of time - in seconds or minutes. The computer has made such laborious methods practical and attractive and has acted as a spur in research and development of approximate methods in general.

One such method or technique which is particularly attractive to the designer because of its wide range of application is called Finite Element Analysis. It can be applied to problems in stress/strain, fluid flow, temperature, pressure and heat flow, instability and vibration.

It is useful in examining the F. E. method to draw comparisons with an allied technique known as finite difference analysis. In the latter method the governing differential equation is replaced by an approximate expression in terms of the ordinate values.

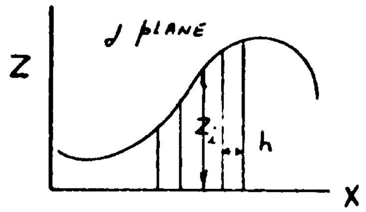


FIG. 6

$$\frac{\partial z}{\partial x_{i,j}} = \frac{z_{i+1,j} - z_{i-1,j}}{2h}$$

$$\left.\frac{\partial z}{\partial x}\right|_{i,j} = \frac{1}{2h}\left\{ \underset{i-1,j}{(-1)} \text{—} \underset{i,j}{(0)} \text{—} \underset{i+1,j}{(+1)} \right\}$$

$$\left.\frac{\partial z}{\partial y}\right|_{i,j} = \frac{1}{2k}\left\{ \begin{array}{l} (+1)_{i,j+1} \\ \quad | \\ (0)_{i,j} \\ \quad | \\ (-1)_{i,j-1} \end{array} \right\}$$

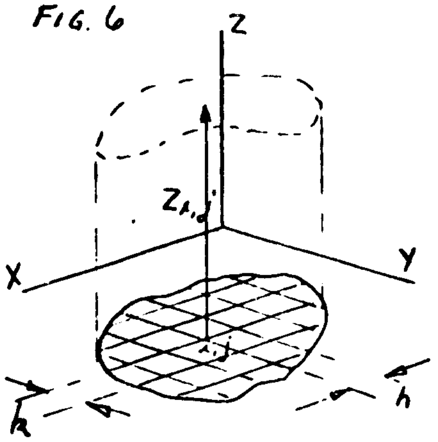


FIG 7.

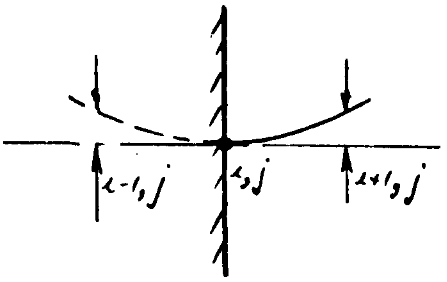
$$\left.\nabla^4 z\right|_{i,j} = \frac{1}{h^4}\left\{ \begin{array}{ccccc} & & (+1) & & \\ & (+2) & (-8) & (+2) & \\ (+1) & (-8) & (+20)_{i,j} & (-8) & (+1) \\ & (+2) & (-8) & (+2) & \\ & & (+1) & & \end{array} \right\} \quad k = h$$

These are a few of the standard approximate forms expressed in a convienient grid format. There are also forms available which handle grid arrangements at boundaries involving irregular spacing, forward and backward differences etc.

For each grid point i, j, one can construct an equation involving only ordinate values $Z_{l,m}$. Assembling these for all the points produces a set of simultaneous equations.

$$|K|\{Z\} = \phi$$

Boundary conditions are then introduced which specify the value of Z, $\frac{\partial z}{\partial x}$ AND $\frac{\partial z}{\partial y}$ on the boundary



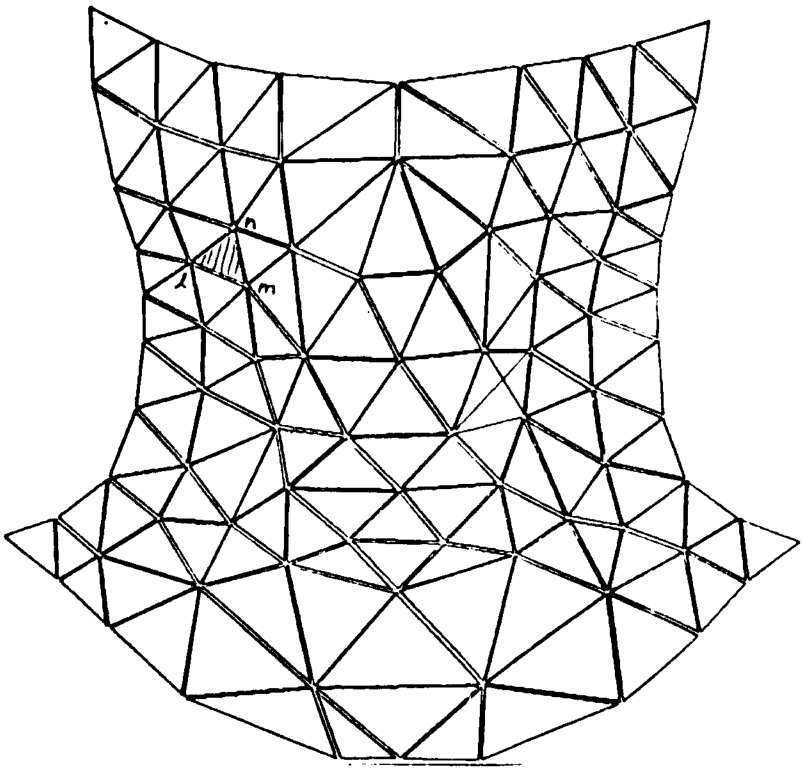
REAL BOUNDARY

e.g. $\frac{\partial z}{\partial x}_{i,j} = 0$

$\longrightarrow Z_{i+1,j} = Z_{i-1,j}$

It is now possible to use some iterative methods to solve for the values of Z at each node or grid point. With this technique however, boundary conditions and shape can present some problems.

In contrast the FINITE ELEMENT method subdivides the component or the surface or the problem space into discrete physical elements or domains. These are linked or connected only at discrete points or nodes. The shapes of the elements varies with the particular application but the simplest shape is the triangular element. In this the interconnection only exists at the three corner points i, j, k. See fig. (8).



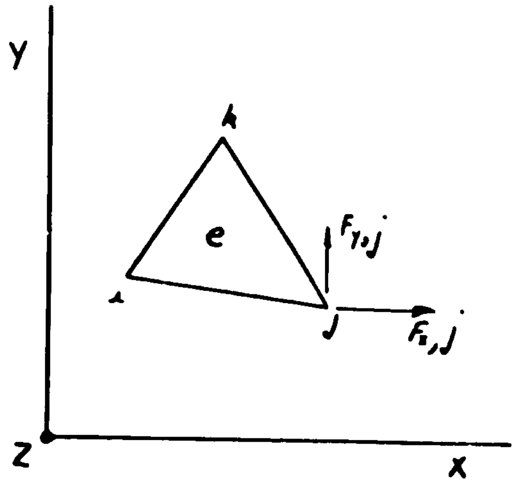


Fig 8

For each discrete triangular element it is possible to relate quanitities at the nodes in a simple manner.

$$\{\xi\} = [K]\{\phi\}$$

This concept was first developed for two dimensional stress problems where this equation represented the relationship between nodal forces F and displacement δ as follows.

$$\{F_x, F_y\}_{i,j,k} = [K]\{\delta_x, \delta_y\}_{i,j,k}$$

where

$[K]$ is a 6 x 6 matrix of stiffness coefficients determined on the basis of a uniform stress system within the element and by equating the external and internal work done by the forces and stresses during arbitrary nodal displacements.

Many other element forms have been devised to cope with the many different situations in which the method is used to effect an approximate solution. Some of the element shapes which have become popular are shown below.

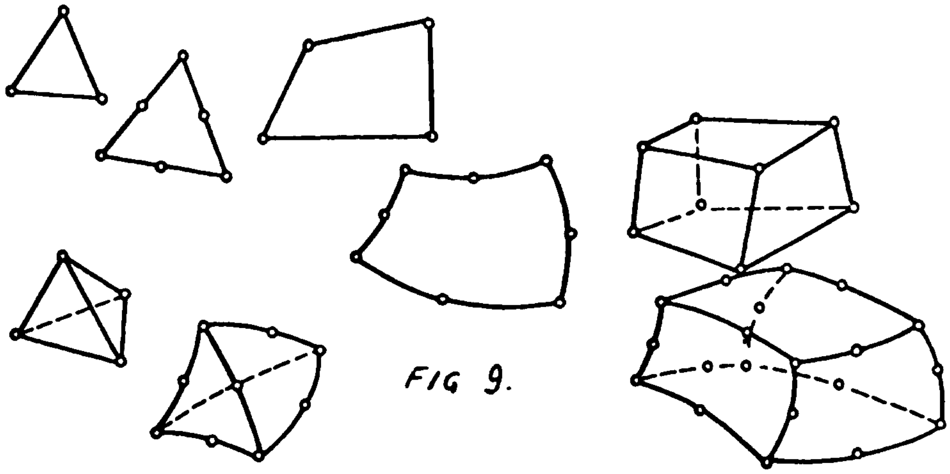


FIG 9.

Several elements are usually joined at each node throughout the continuum so that the force components at each node can be summed to obtain the equation for the resultant force at each node. This is how the total set of n simultaneous equations for the n nodal points is assembled.

$$\{F\}_n = [K]_{n,n}\{\delta\}_n$$

where $[K]$ is a sparsely populated n x n matrix of nodal point stiffness coefficients.

In this state the stiffness matrix is singular and requires to be modified to include the boundary conditions before a solution can be obtained. This is simply done by inserting the known nodal forces or displacements, partitioning the matrix and solving for the unknown displacements.

$$\{F_k \quad F_u\} = \left[\begin{array}{c|c} K_{11} & K_{12} \\ \hline K_{21} & K_{22} \end{array}\right]\{\delta_u \quad \delta_k\}$$

where the suffices K,u refer to known and unknown values

$$\{F_k\} = [K_{11} \quad K_{12}]\{\delta_u \quad \delta_k\}$$

$$\{\delta_u\} = [K_{11}]^{-1}\{F_K - K_{12}\delta_K\}$$

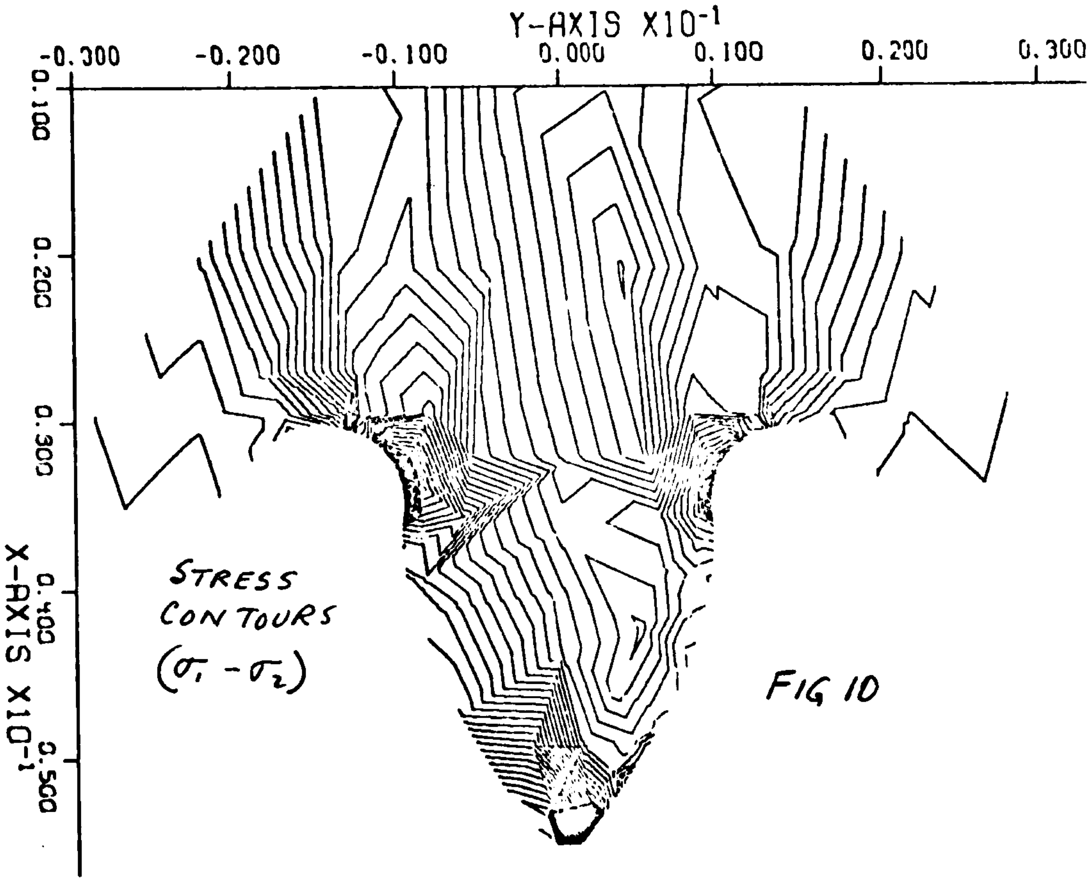
which is the unknown displacements and

$$\{F_u\} = [K_{21} \quad K_{22}]\{\delta_u \quad \delta_K\}$$

which is the boundary forces.

$$= [K_{21}]\{\delta_u\} + [K_{22}]\{\delta_K\}$$

these can be fed back to the individual elements themselves to determine the stress system within them (based on the initial stress conditions assumed on setting up the stiffness matrix). The results can be displayed in tabular form or more usefully in graphical form as indicated below. Fig 10



STRESS CONTOURS $(\sigma_1 - \sigma_2)$

FIG 10

An alternative method of formulating the finite element problem is by the use of the Variational Calculus. By this method a partial differential equation - for example the following second order equation -

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + C = 0$$

applicable over a region V and having prescribed boundary values $\phi = \phi_B$ can be transformed to the equivalent mathematical problem of finding a function ϕ which minimises the functional

$$\chi = \iint_V \left[\frac{1}{2}\left(\frac{\partial \phi}{\partial x}\right)^2 + \frac{1}{2}\left(\frac{\partial \phi}{\partial y}\right)^2 - c\phi \right] dx\, dy$$

and satisfies the same boundary condition i.e.

$$\frac{\partial \chi}{\partial \phi} = 0$$

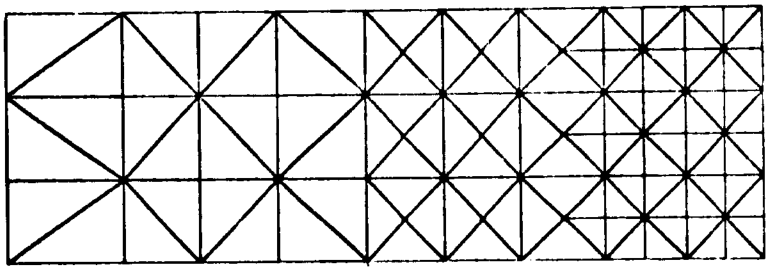
For each finite element the value of ϕ can be desceibed in terms of the nodal values ϕ_i, i = 1,n as

$$\begin{aligned} \phi &= \left| N_i, N_j, N_k \text{ ---} \right| \left\{ \phi_i \;\; \phi_j \;\; \phi_k \text{ ---} \right\} \\ &= \left| N \right| \left\{ \phi \right\}^e \end{aligned}$$

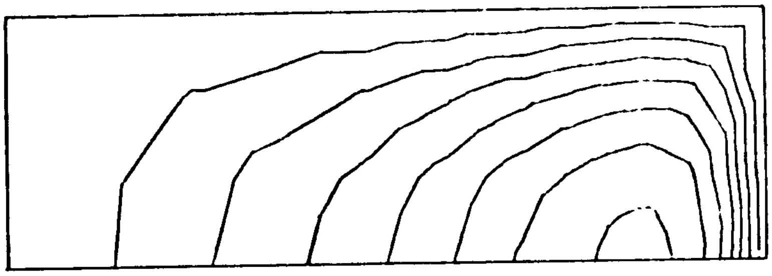
where $\{\phi\}^e$ is a list of parameters - i.e. ϕ at nodes i, j, k ---

$$\frac{\partial \chi^e}{\partial \phi_i} = \iint_{V^e} \left[\frac{\partial \phi}{\partial x} \frac{\partial}{\partial \phi_i}\left(\frac{\partial \phi}{\partial x}\right) + \frac{\partial \phi}{\partial y} \frac{\partial}{\partial \phi_i}\left(\frac{\partial \phi}{\partial y}\right) - c\frac{\partial \phi}{\partial \phi_i} \right] dx\, dy$$

$$\begin{aligned} = \iint \Bigg[&\left(\frac{\partial N_i}{\partial x}\phi_i + \frac{\partial N_j}{\partial x}\phi_j + \cdots \right)\frac{\partial N_i}{\partial x} + \\ &\left(\frac{\partial N_i}{\partial y}\phi_i + \frac{\partial N_j}{\partial y}\phi_j + \cdots \right)\frac{\partial N_i}{\partial y} - cN_i \Bigg] dx\, dy \end{aligned}$$



ARRANGEMENT OF ELEMENTS



PRESSURE CONTOURS

SCALE X

1.0

SCALE Y

1.0

SCALE P

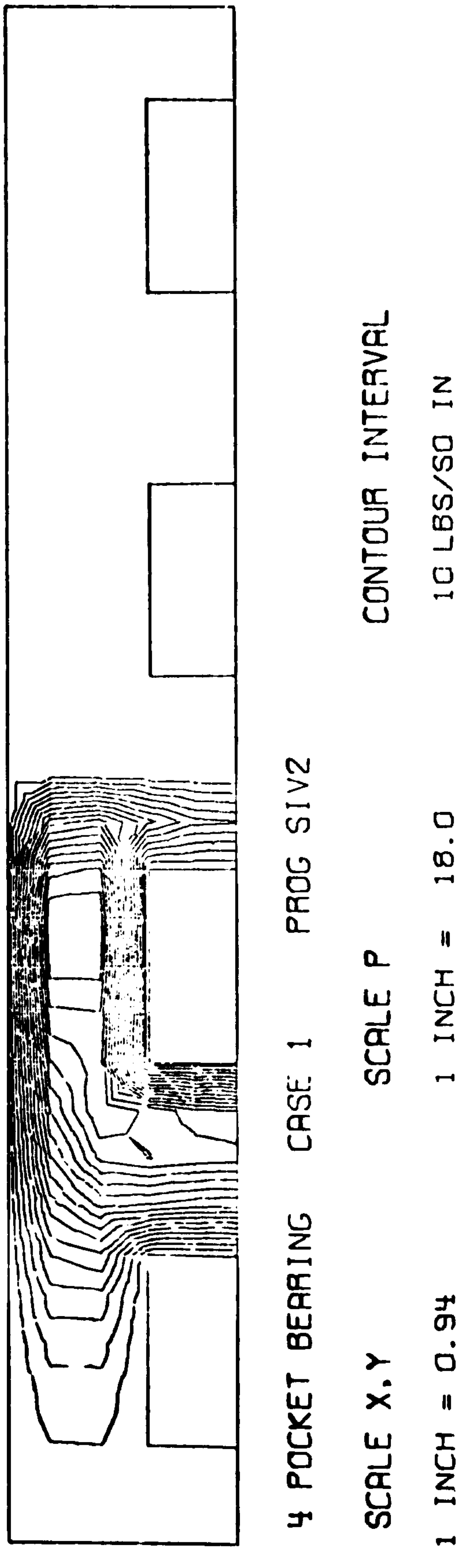
0.002

CONTOUR

1.0

FIG. 11

HYDRODYNAMIC BEARING.



PRESSURE CONTOURS FOR A FOUR POCKET HYDROSTATIC BEARING USING FINITE ELEMENT ANALYSIS.

FIG. 12

$$\frac{\partial V^e}{\partial\{\phi\}^e} = |K|^e \{\phi\}^e + \{F\}^e$$

WHERE

$$k_{l,m} = \iint_{V^e} \left(\frac{\partial N_l}{\partial x}\frac{\partial N_m}{\partial x} + \frac{\partial N_l}{\partial y}\frac{\partial N_m}{\partial y} \right) dx\,dy$$

$$F_l = -\iint_{V^e} C . N_l \, dx\,dy$$

Note that the problem is transformed from a second order differential equation to a first order differential form with integration.

Once the "stiffness" matrix values have been obtained for the element they can be assembled in the normal way for the total domain. Boundary values can then be inserted and normal iterative solutions obtained. Some examples of the applications are given below.

a) Hydrodynamic Bearing (Fig. 11)

b) Hydrodynamic Pocket Bearings (Fig. 12)

These are what are known as field problems where the results indicate the variation in a particular quantity, i.e. pressure, temperature etc. over a zone of interest. The first (a) shows the pressure contours on a symmetrical half portion of an oil lubricated journal bearing. The second (b) shows a development of the same technique to include recessed pockets in the bearing which are supplied with oil through a small capillary restrictor. There one can investigate the effects of pocket size and position, supply pressure and restrictor diameter, and bearing eccentricity and rotational speed on the load capacity.

Substructure arrangements and matrix partitioning

It frequently happens that in the search for greater accuracy or in the desire to analyse larger and more complicated components we incorporate too many elements for the size of computer available. The alternative to reducing the number of elements is to use a system of substructuring (see Fig. 13). In this the structure is subdivided in portions containing a reasonable number of elements each (see fig. 14). The nodes on the boundaries between each substructure are indicated by dots(•) and are known as active nodes. The nodes inside each substructure which carry zero external forces are dormant noded and we eliminate these by a process of matrix partitioning

e.g. if F_A & δ_A is the active nodal force and displacement vectors

and F_D and δ_D is the dormant nodal force and displacement vectors

then
$$\left\{ F_A \; F_D \right\} = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \left\{ \delta_A \; \delta_D \right\}$$

$$\left\{ F_D \right\} = \left[K_{21} \right] \left\{ \delta_A \right\} + \left[K_{22} \right] \left\{ \delta_D \right\}$$

but $c_D = 0$

$$\therefore \left\{ \delta_D \right\} = \left[K_{22}^{-1} \; K_{21} \right] \left\{ \delta_A \right\}$$

hence
$$\left\{ F_A \right\} = \left[K_{11} + K_{12} \, K_{22}^{-1} \, K_{21} \right] \left\{ \delta_A \right\}$$

$$= \left[K \right] \left\{ \delta_A \right\}$$

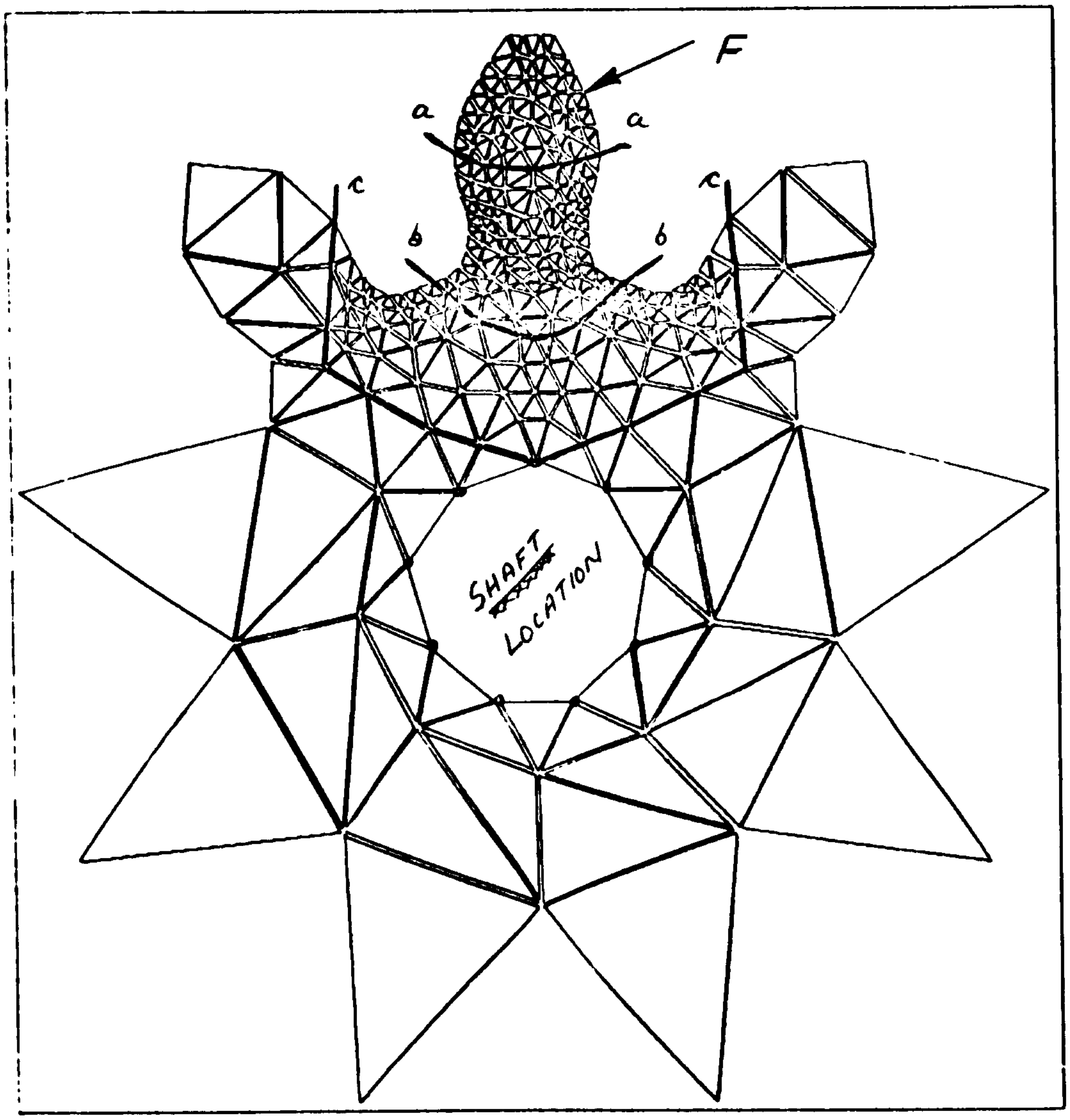
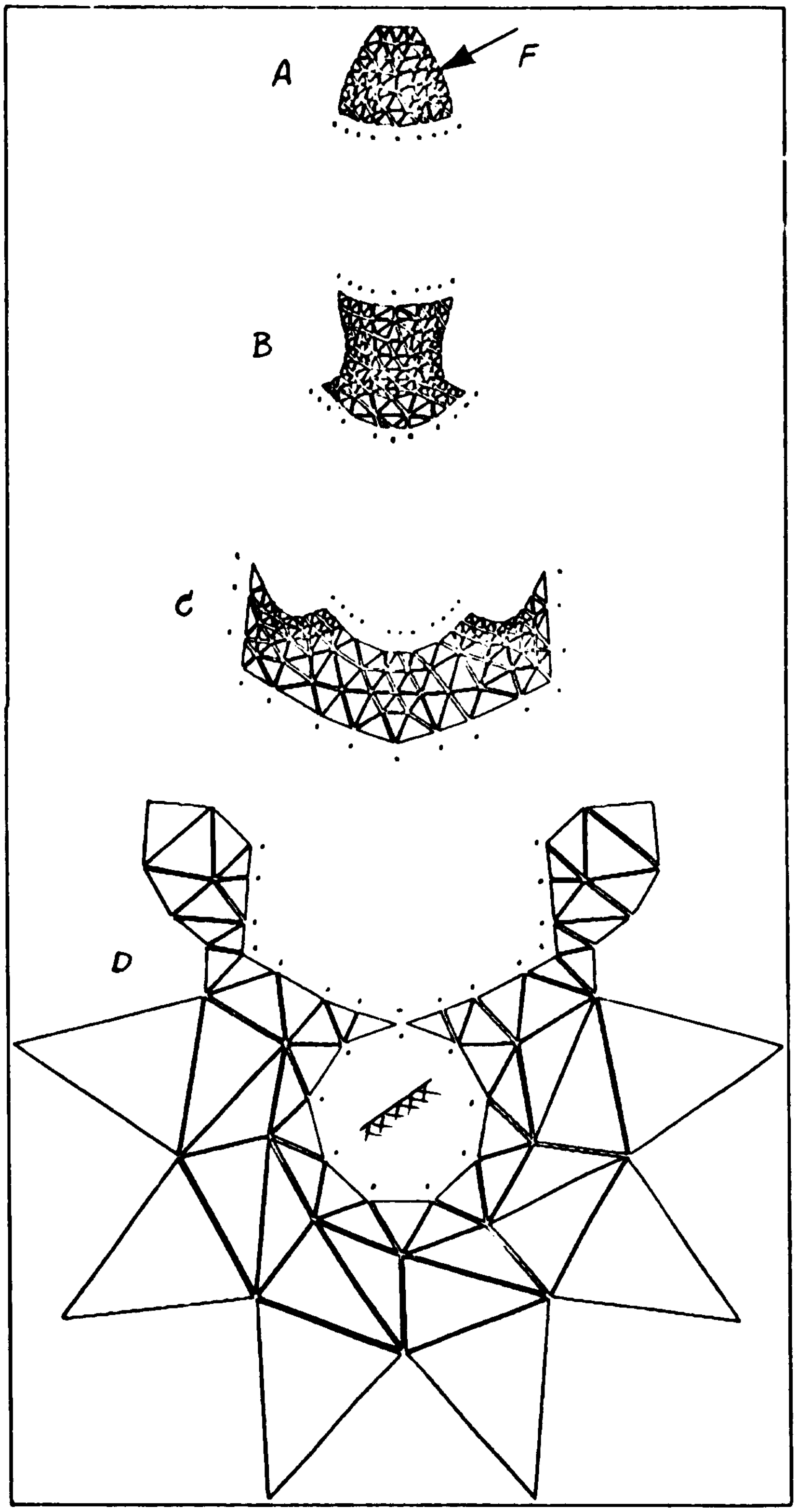


FIG. 13

ASSEMBLY OF ELEMENTS



FOUR SUBSTRUCTURES

FIG. 14

The size of the matrix can be reduced from (A+D) x (A+D) to A x A, where $[K]$ becomes the stiffness of a more sophisticated or super element. These super elements are now assembled in the normal manner, boundary conditions imposed and a displacement solution obtained for the nodes on the substructure boundaries. These are then used as boundary conditions for the superelements themselves to obtain the detailed solution for the actual basic elements.

Finite Element Packages

The finite element analysis system has been greatly developed and extended over the past ten years. Hundreds of man-years of effort have been expended to produce a number of large general purpose and special purpose packages. Some of those more commonly available are listed in fig. 15. These packages usually allow the user to incorporate a variety of different types of elements, two and three dimensional elements, plate elements and beam elements. In most cases, however, the instructions to use these packages occupy several volumes which can take one some little time to master and become efficient in their use. It is also important to understand the basis on which each package is developed in order that the results can be interpreted in a meaningful way.

Because of the general applicability of many of the packages they are very large and fairly expensive to use. Care must therefore be excercised to apply such packages to problems where such high costs are justified. This also generally means that experience is desirable and training of new personnel to use the packages essential.

FINITE ELEMENT PACKAGES.

Package name.	Originator & suppliers in Europe.	Year started.	Man yrs of development.	Remarks.	Bureau availability.	Machines mounted on. CDC 6600/7700	Univac 1100s	IBM 360/370	Others	Number of Elements.	Heat transfer and fluid flow availability.	Pre and post processors.
NASTRAN	Nasa Suppliers for Europe — MacNeal-Schwendler Corp. of Munich.	64	100+	US Government funded. Designed for dynamic analysis for US space program. Cartainly the biggest, in some ways, the best.	SIA UCC/Wates IBM Data Centre.	Y	Y	Y	IBM 7094 7040	45	Heat transfer.	Automatic numbering systems, dynamic analysis, Wates trying to form library of post processors. Good plotting including: structure; displaced structure, stress & displacement contours; X — Y output for transient and frequency response.
SESAM-69	Det Norske Veritas & Institute of Static, University in Trondheim, Norway. A/S Computas, Oslo.	64	100+	Originally designed for marine structures hence large capacity & excellant sub-structures.	SIA	Y	Y	?		14	Other packages.	Input data; displaced structures; iso stress curves; stress diagrams.
ASKA Automatic System for Kinetic Analysis	Under direction of Prof. J H Argyris Institut fur Statik und Dynamik, Stuttgart.	64	100+	The first available package with a large analysis capability.	SIA	Y	Y	Y		40+	No.	
MARC-CDC	Marc Analysis Corp. (USA).	??	100+	A large US package rumoured to be expensive. Recently offered in UK.	CDC	Y				23	Available.	General purpose finita element plotting package. (2-3 dimensions, contours, time history plots etc.)
STARDYNE	Mechanics Research Inc.	??	100+	As above. The dynamic package.	CDC	Y				14	In Marc.	Automatic numbering systems General plotting progrs. Model siza reduction. Timer program for run estimates.
ASAS Atkins Stress Analysis System.	Atkins Research & Development (Atkins)	69	50+	Unusual in being developed from conception as a truly general purpose systam, easy-to-use; well documentad. Originally DOE funded.	Atkins Computing Services.	Y	Y	Y	ICL 1900 Xarox	40+	Associated or integrated.	Input plotting facilities. Output plotting also available.
BERSAFE	Central Electricity Generating Board, under direction of T K Hellen.	67/8	6+	Grown from CEGB's internal requirements. Wide range of applications. Good graphics for UK package.	CEGB	Y				32+	Seperate progs. Fluid work going on.	Certain fracture mechanics work. Aiming to do away with output at main calculation time.
CONSAS Constrado Structural Analysis System.	Structures & Computers Dr P K Lim, Dr K R Moffatt (Constrado is the British Steel R & D organisation).	??	10	A promising newcomer. Already been used on a number of projects. Large steel and concrete structures.	Wates/UCC	Y	Y		IBM 7094 Atlas	50	None	Sectional plots of displacements, stresses and reactions. Loadcase combinations.
PAFEC 70+	Mechanical Engineering Dept, University of Nottingham.	69/70	50+	Anothar newcomer Has quickly found acceptance. Hopefully they can get a bureau interested.		Y	Y	Y	DEC 10 ICL 1900	60+	Available.	General plotting facilities.
FINESSE	Prof Zienkiewicz's group, University of Swansea. Available through Software Licencees.	67	25	A good medium size program which has suffered from lack of technical support in recent years.	Available at SIA	Y	Y			??	Available.	Some plotting facilities & little else.

Table shows rough positions in the field. The lines drawn across are intended to indicate a similarity in the packages within each group.

FIG. 15

Non-Linear Problems

In recent years considerable attention has been directed to solving non-linear behaviour by the finite element methods. These are concerned with geometric non-linear behaviour, material non-linear behaviour or a combination of both. Thus problems involving the stability of structures and continua are being tackled by this technique. Although fairly involved the method extends the common philosophy of the F. E. technique and for example in the geometric non-linear case uses the same basic processes, i. e.

(a) Total Energy potential:-

$$M = q^T \left(\tfrac{1}{2} K + 1/6\, N_1 + \frac{1}{12} N_2 \right) q - q^T P$$

(b) the equilibrium equation

$$(K + \tfrac{1}{2} N_1 + \tfrac{1}{3} N_2) q - P = (O)$$

and
(c) the linear incremental equilibrium equation

$$(K + N_1 + N_2) \Delta q - \Delta P = (O)$$

where K is the linear stiff matrix as before and N_1 and N_2 are the first and second order geometric stiffeness matrixes (non-linear effects)

The finite element method can obviously be applied to a tremendous variety of engineering problems and result in a degree of understanding and knowledge of structural and component behaviour previously only possible (sometimes) with extensive experimental investigation. The fact that it is embodied in a common philosophy and approach makes it an attractive tool for the design engineer to study and use.

The Graphical Phase

Drawing and/or graphical representation plays a major role in mechanical engineering design and production. It is used as a communication medium, as a back up store to the human mind and as a problem solving technique. When the pen or pencil-is attached to a "human" computer he uses computing techniques and specialised hardware which have been specially evolved and devised to suit his mental powers and his input/output peripherals. When the pencil is connected to a computer which uses binary logic, the hardware and software have a number of significant differences. To discuss these it will be convenient to confine our attention mainly to the paper plotter and other devices such as those which use a cathode ray tube and basically adopt the same philosophy.

The drawing devices are simply numerically controlled machine tools - controlled by binary pulses. There is, as in all computer systems, a high level language and compiler to enable the programmer to set out his instructions in a program in an easily understood form.

For example

OPENGP

Instructs the computer to link in the plotting device

HGPLOTT (X,Y,IC,L)

is a general instruction to move the pen to co-ords X, Y, IC is the pen indicator and L is a mode option - full line, chain dotted, assign origin, etc.

HGPCIRCLET (X, Y, THO, THF, RD, RF, DI)

is used to generate a circle or spiral

These give the general idea of what most languages involve. These are really the names of SUBROUTINES and the symbols inside the brackets are what are called DUMMY VARIABLES, i.e. any variable name can be substituted for those given.

ex

HGPLOTT (VEL, TIM, JJ, O)

A storage tube graphics device would use something like the following

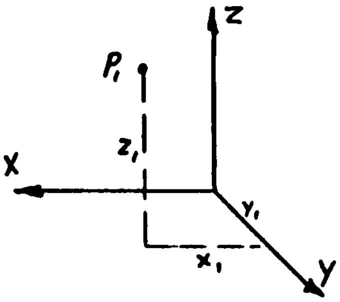
BEGIN (JBAUD, MODEL)
ERASE
VECTOR
SCALE (XFACT, YFACT, XORG, YORG)
TPLOT (X, Y, IPEN, MARK) etc.

which are almost self explanatory.

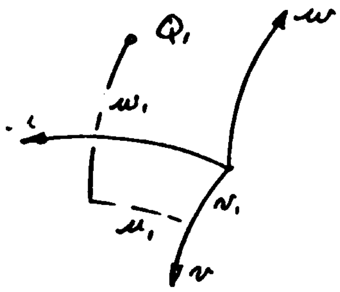
The language is therefore very simple to use so the effort in graphics is concentrated on devising and organising the actual analytical geometry.

(a) Three Dimensional Space and Mapping

A physical body occupies 3-dimensional space and points on it can be defined or located by three co-ordinates. These, in general, can be curvilinear but the most common form and initially the most useful is linear orthogonal co-ordinates.



Orthogonal



Curvilinear

Each point in space can be identified by three numerical constants.

$$P_1 \rightarrow X_1,\ Y_1,\ Z_1 \qquad \text{or} \qquad Q_1 \rightarrow u_1,\ v_1,\ w_1$$

Other constants can also be added in sequence to convey further information or instructions, e.g. drawing instructions could be incorporated by using integers as follows:

-1 to signified an origin
0 " " no trace or pen up
1 " " visible line or pen down

The following sequence would give the instructions for drawing a triangle ABC in space.

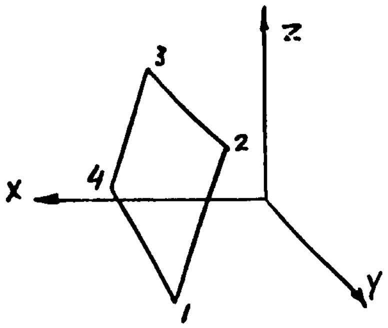
X_0	Y_0	Z_0	-1	origin
X_A	Y_A	Z_A	0	more to point A with pen up (pen at A)
X_B	Y_B	Z_B	1	draw line from A to B (pen now at B)
X_C	Y_C	Z_C	1	" " " B to C (pen now at C)
X_A	Y_A	Z_A	1	" " " C to A (pen now at A)

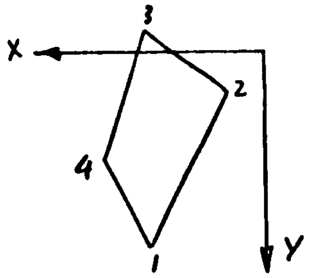
Mapping is the process of translating data from one co-ordinate system to another by some form of rule.

Orthographic Projection is the mapping of three dimensional space to two dimensional space by simply dropping one of the dimensions i. e. each view gives information about two dimensions on the body.

e. g.

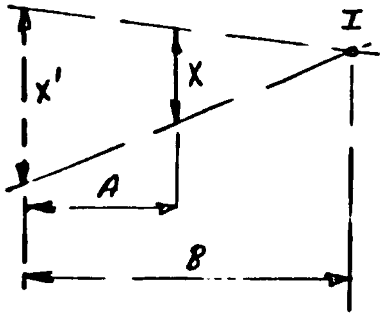
$$\begin{matrix} x_1 & y_1 & z_1 & 0 \\ x_2 & y_2 & z_2 & 1 \\ x_3 & y_3 & z_3 & 1 \\ x_4 & y_4 & z_4 & 1 \\ x_1 & y_1 & z_1 & 1 \end{matrix} \longrightarrow \begin{matrix} x_1 & y_1 & 0 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \\ x_4 & y_4 & 1 \\ x_1 & y_1 & 1 \end{matrix}$$





If we start from two-dimensional views of an object two orthographic views will be required to enable us to reconstitute the three dimensional body.

Perspective Projection



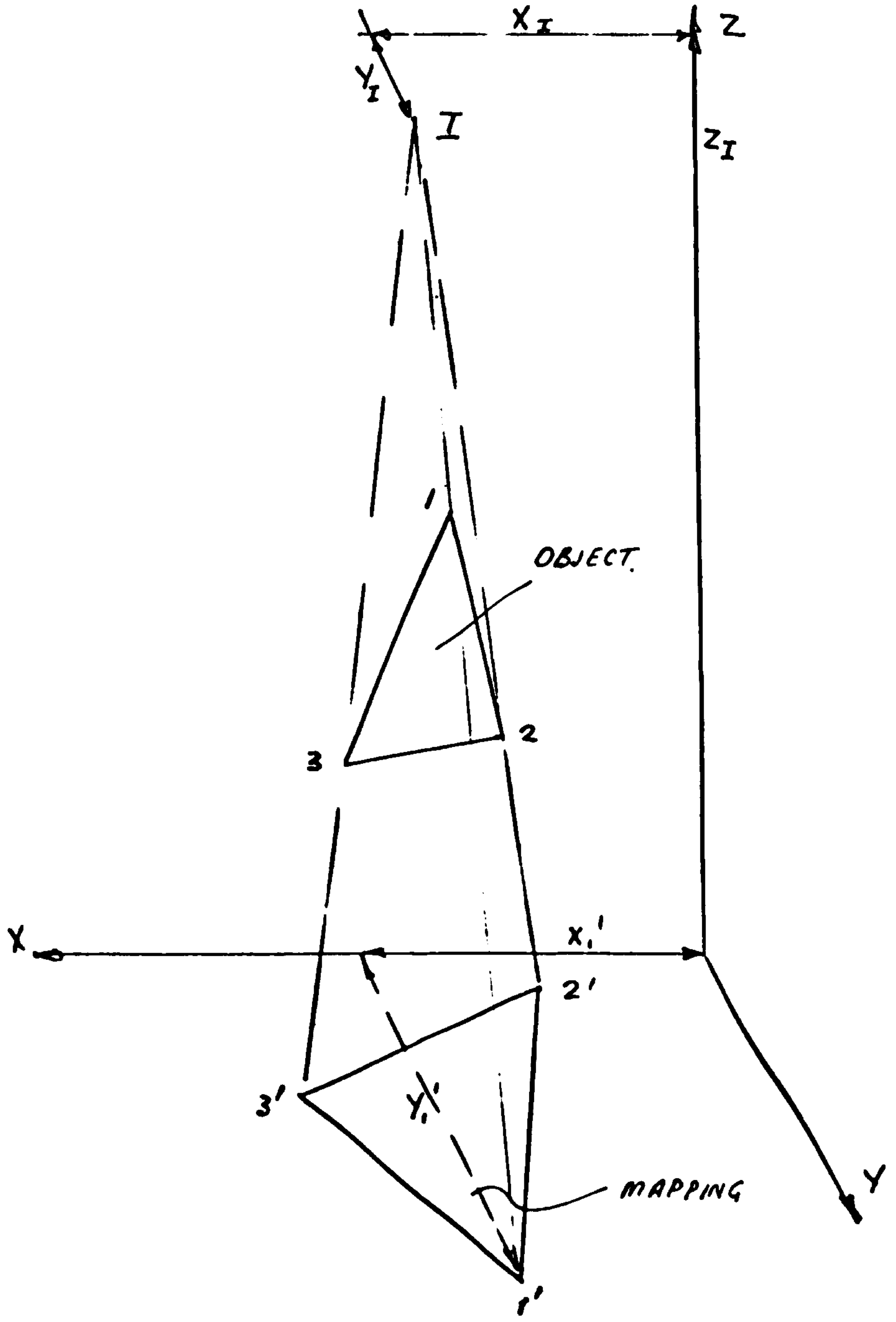
This is a mapping based on that experienced in normal vision - i. e. determined by lines of sight radiating from a focal point such as I.

$$\mu \qquad X \longrightarrow X'$$

$$\therefore X' = X \times \frac{B}{B-A} = \frac{X}{1-\frac{A}{B}}$$

Each point on a body would therefore be transformed or mapped as follows:

$$|X\ Y\ Z\ m| \longrightarrow |X'\ Y'\ m|$$



where $$X' = X_I + \left[\frac{X - X_I}{1 - \frac{Z}{Z_I}}\right] \text{ etc}$$

(b) Data structure for building and modifying drawings

In developing a computer graphics facility which would virtually give characteristics similar to manual draughting one must introduce a structured data system. This is necessary in order to provide the following basic capabilities.

(a) parts of the picture have to be linked together, wo that when one point, line or subpicture is added or moved the adjoining elements are suitably adjusted.

(b) when an item is deleted the relationships between the remaining parts must be updated

(c) the ability to define and delete subpictures

Thus a full data structure must contain more than simply the geometrical 'points and lines' information. It must also include application data and the hierarchy of picture parts and their inter-relationship. Special languages are available, e.g. AED and APL which automatically assemble the data in this structured form and allow deletions and alterations.

However, a simple data structure can be organised using a high level language such as FORTRAN. In such systems arrays are used to store the data and its relationships, e.g. a drawing can be considered as points linked as in fig 16 which involves a matrix of co-ordinates and a matrix of pointers. This can be easily extended to include circles and sub-drawings.

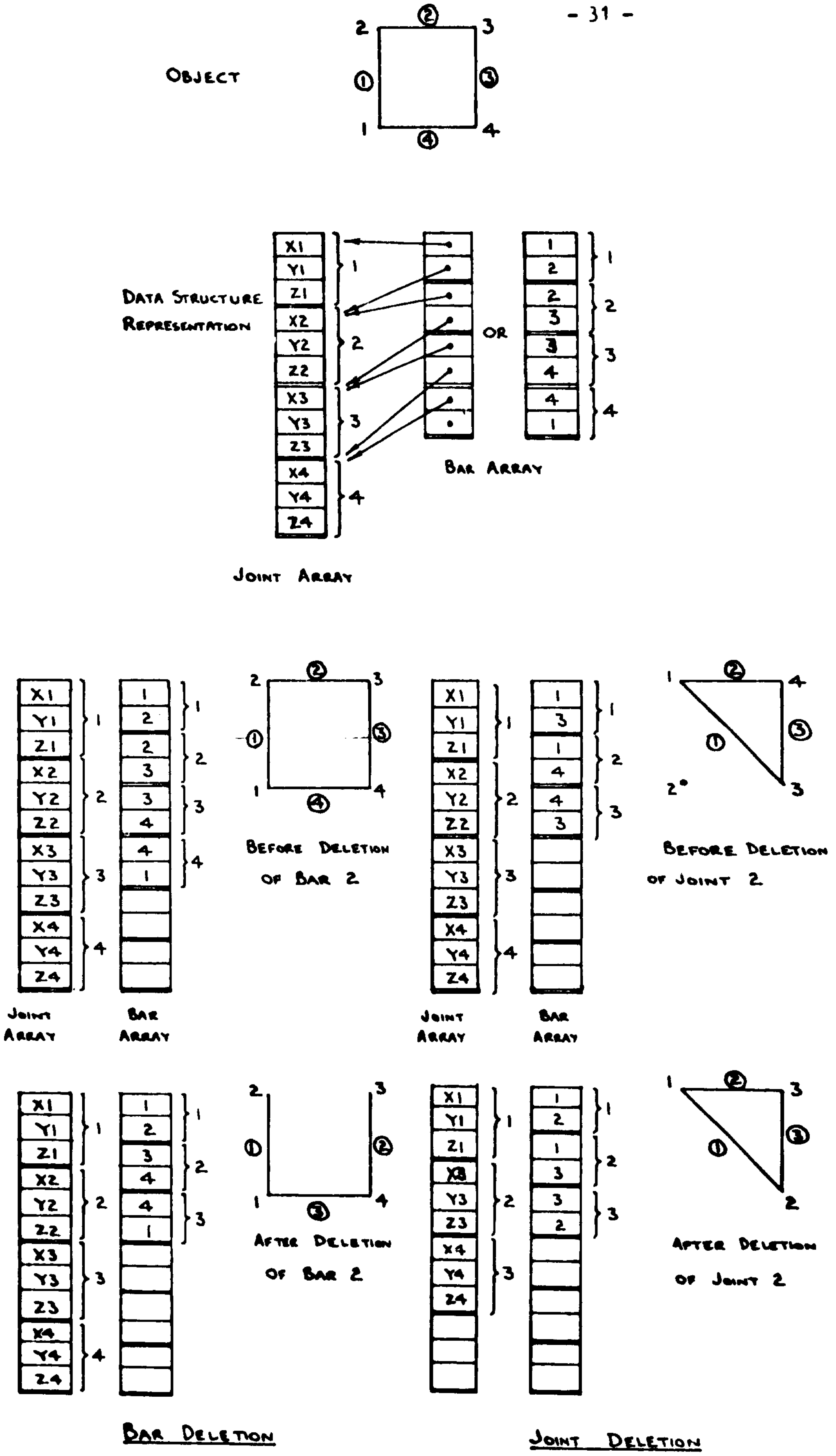


FIG 16 SIMPLE DATA STRUCTURE

(c) Menu System for Assembly Drawings

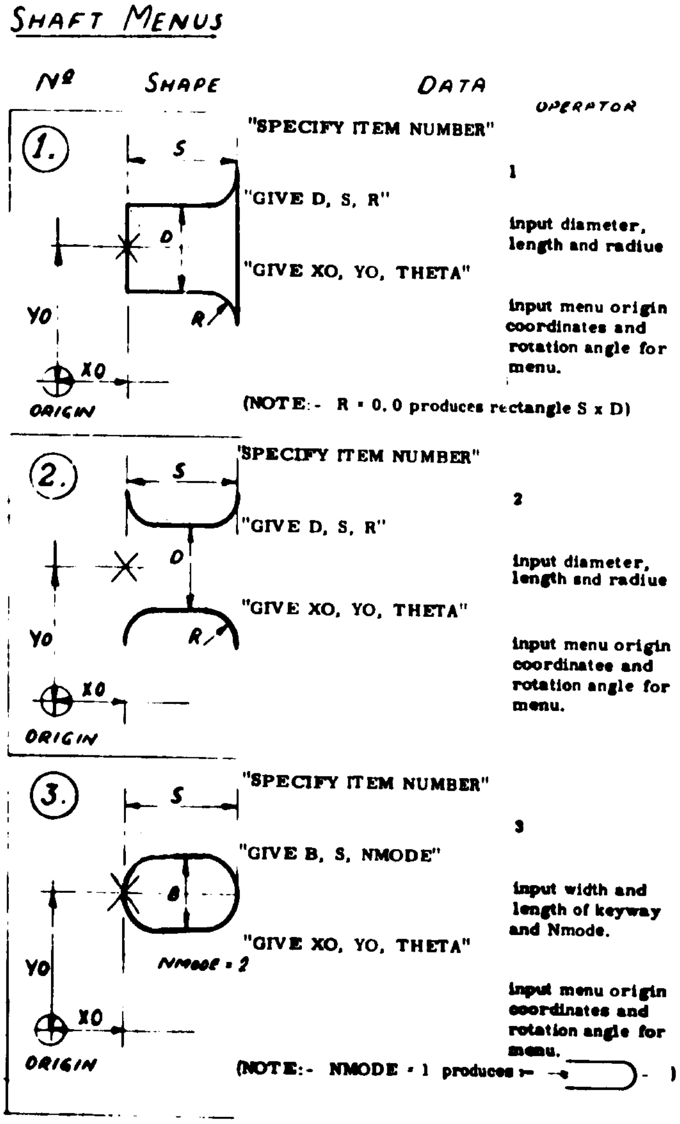
Many engineering drawings are composed of sub-drawings which are repeated with different orientations and sizes, many times over. By analysing a particular family of engineering component drawings, one can produce a list or MENU of these basic geometrical forms. These shapes can then be scaled and positioned in the appropriate order to produce the complete unit.

Each basic shape will reside in its own SUBROUTINE. This will incorporate the basic data and drawing sequence and will allow the required translation and rotation to position the shape accurately. The actual drawing subroutines HGPLOT or TPLOT etc. can either be included in each MENU SUBROUTINE or arranged in a special drawing subroutine which can be CALLED after the shape routine has been executed.

A MASTER PROGRAMME is then used to assemble the various shapes in the appropriate order to produce the complete drawing. This programme is used to facilitate the input of dimensions and other data appropriate to this one component of the total family of components that the programme can handle.

The user of course need know nothing of these details. He simply follows a listing of instructions. This indicates the shapes involved, the request for data that appear at the central terminal and the responses which the user should make on the keyboard or screen.

A simple example of such an instruction is shown below



Nº	Data	Operator
1.	"SPECIFY ITEM NUMBER"	1
	"GIVE D, S, R"	input diameter, length and radius
	"GIVE XO, YO, THETA"	input menu origin coordinates and rotation angle for menu.
	(NOTE:- R = 0.0 produces rectangle S x D)	
2.	"SPECIFY ITEM NUMBER"	2
	"GIVE D, S, R"	input diameter, length and radius
	"GIVE XO, YO, THETA"	input menu origin coordinates and rotation angle for menu.
3.	"SPECIFY ITEM NUMBER"	3
	"GIVE B, S, NMODE"	input width and length of keyway and Nmode.
	"GIVE XO, YO, THETA"	input menu origin coordinates and rotation angle for menu.
	(NOTE:- NMODE = 1 produces ⊃)	

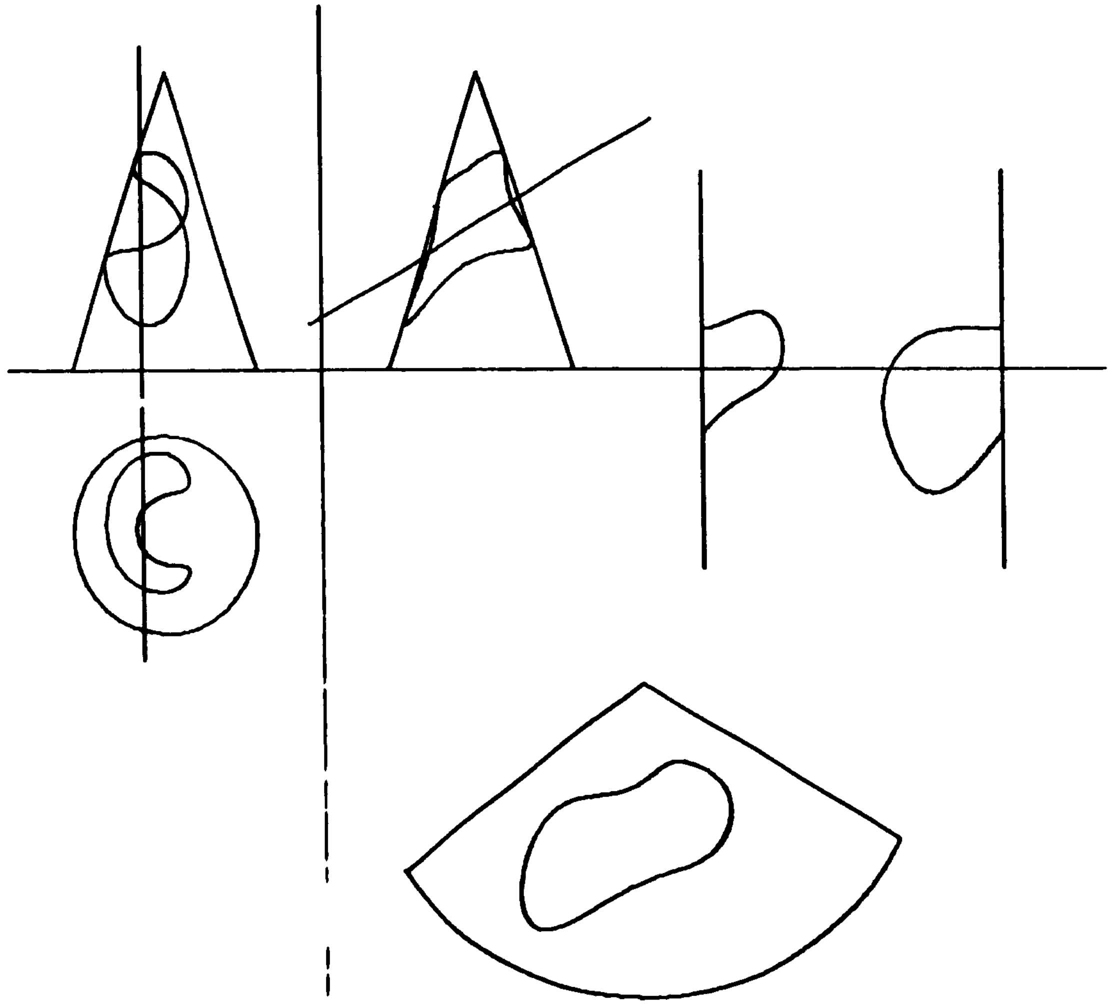


FIG 17

CONE - CYLINDER INTERPENETRATION
AND DEVELOPMENT

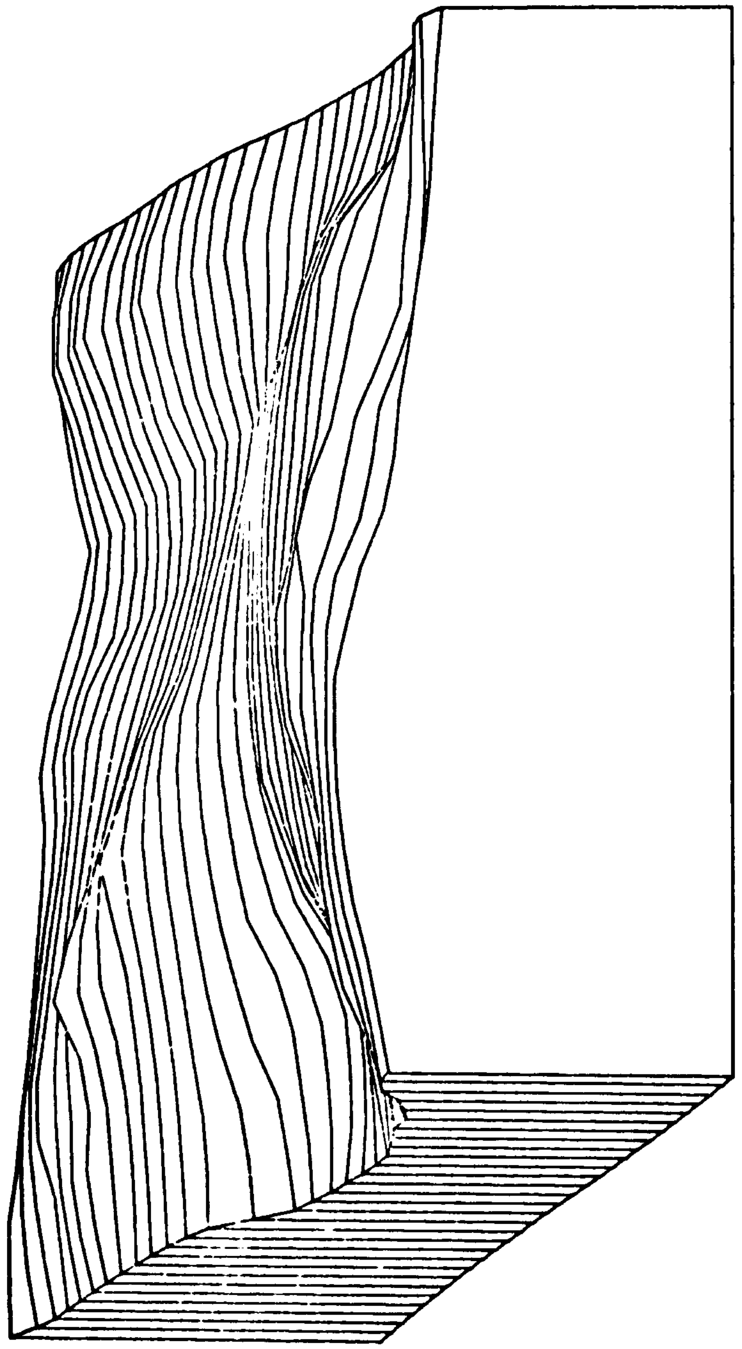
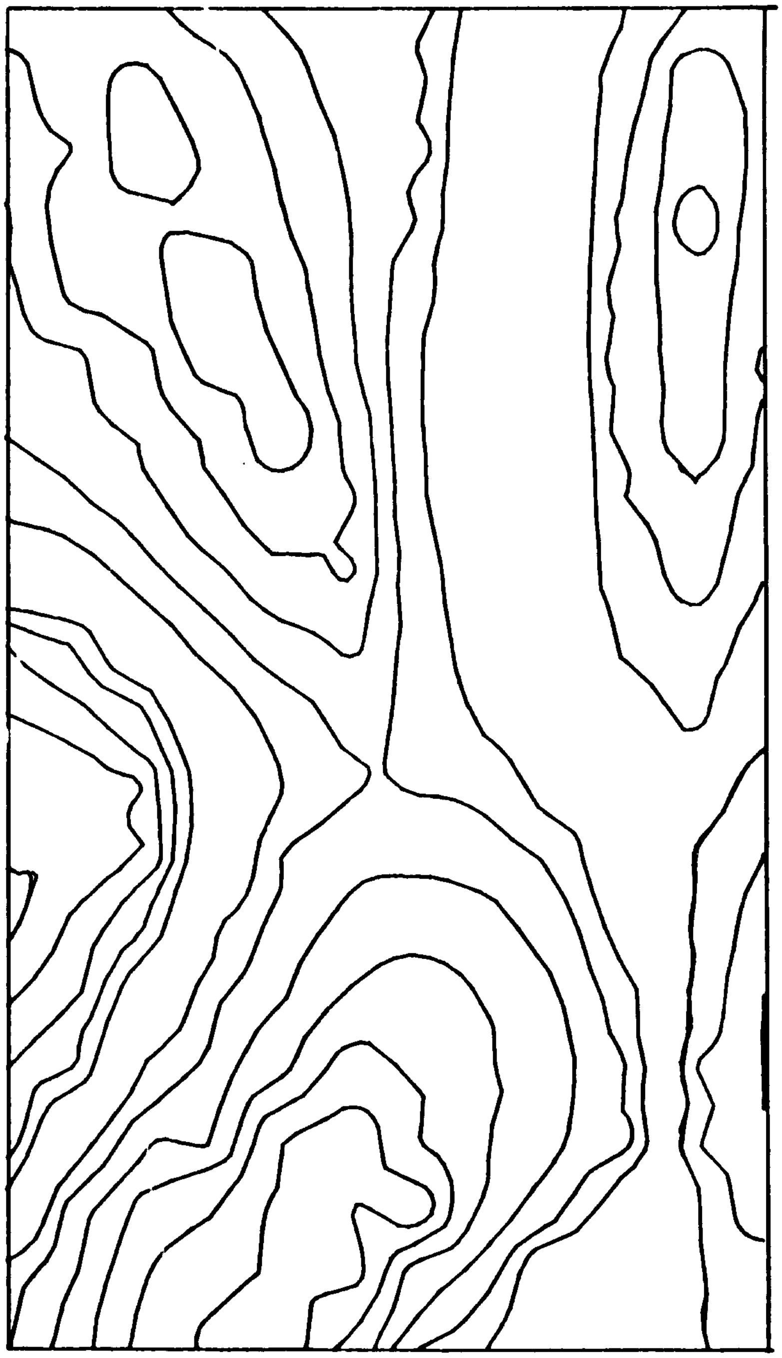


FIG 18
HIDDEN LINE REMOVAL

DP0:CONT3



DP0:CONT3

FIG 19
CONTOURING

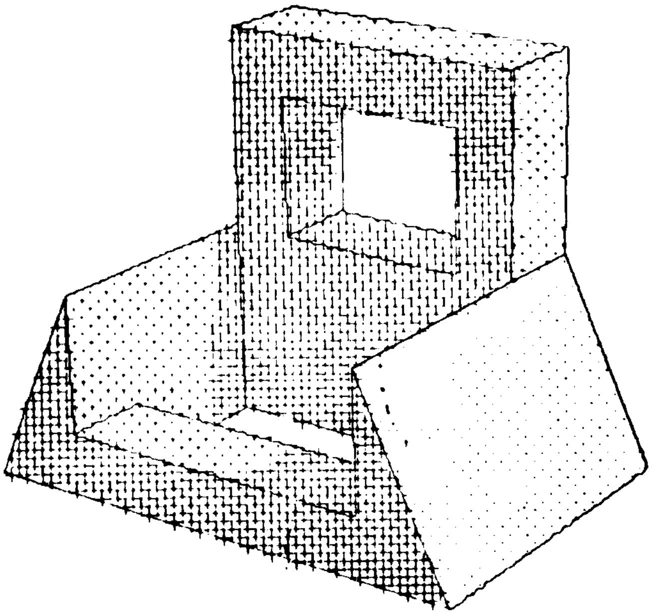


FIG 20
SHADING AND SURFACE TEXTURE

APPEL [illegible]

(d) Analytical Solution for Geometrical Problems

Analytical geometry has received a considerable boost with the development of fast graphical facilities. Some of these involve

1. interpenetration of bodies
2. hidden line removal
3. contouring
4. shading and surface texture

Some examples of these are illustrated in the following pages (figs 17 - 20)

Curves and surfaces also have received a great deal of attention, noteably by Bezier and Coons. Bezier for instance defines his curves (and surfaces) with the aid of 'open' polygons. This defines the end positions, slopes, etc. so that a resulting curve can be defined and drawn. From an interactive pointing view the technique is akin to a spline (the curve) attached to the polygon nodes by invisible springs. By moving the nodes one can 'feel' the nature of curve shape manipulation. This can easily be extended to higher order curves and also to the joinging of curves. Such joining can be arranged to automatically have slope and curvature continuity if desired.

This technique has also been extended to surface patches and has been used in the French motor industry where it originated. (See figs 21,22,23)

Coons, on the other hand, defines his surface by using nodal rectors (X,Y,Z). These are used to define the position of the four nodal

Fig 21a THIRD ORDER BEZIER CURVE & POLYGON

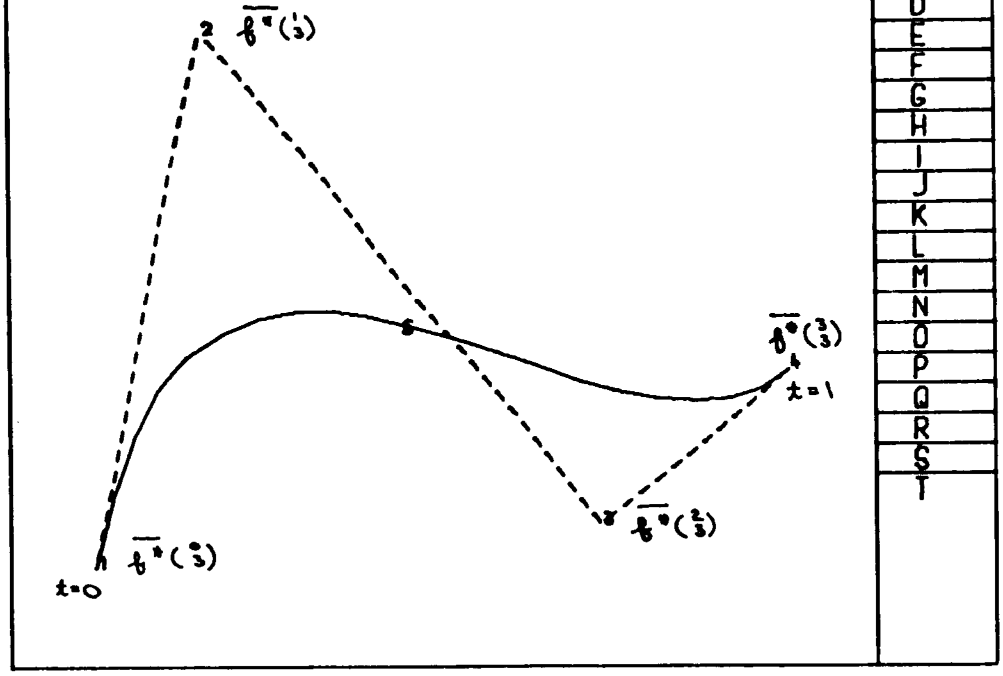
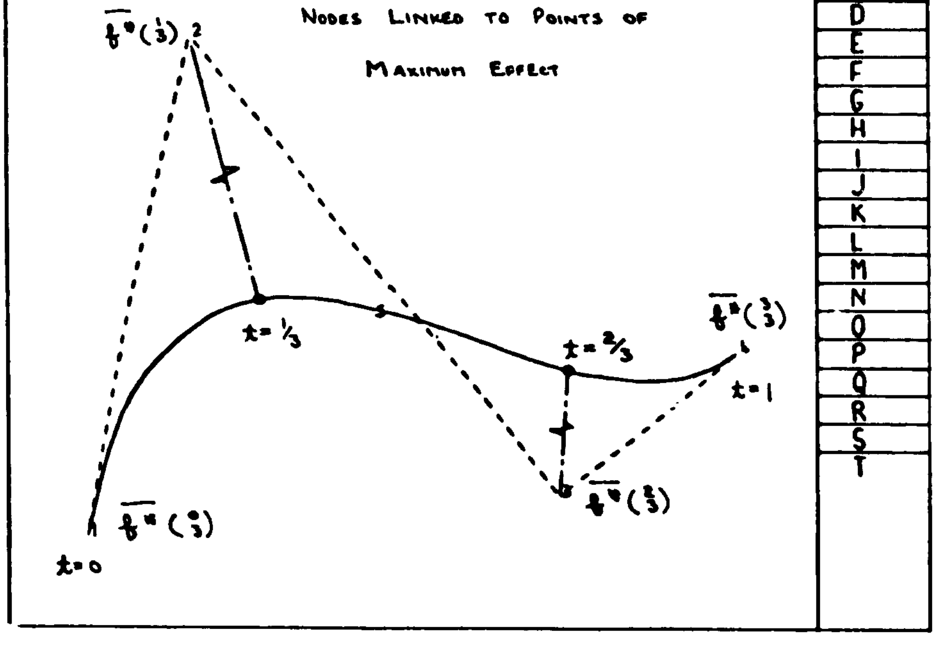


Fig 21 b THIRD ORDER BEZIER CURVE WITH POLYGON NODES LINKED TO POINTS OF MAXIMUM EFFECT



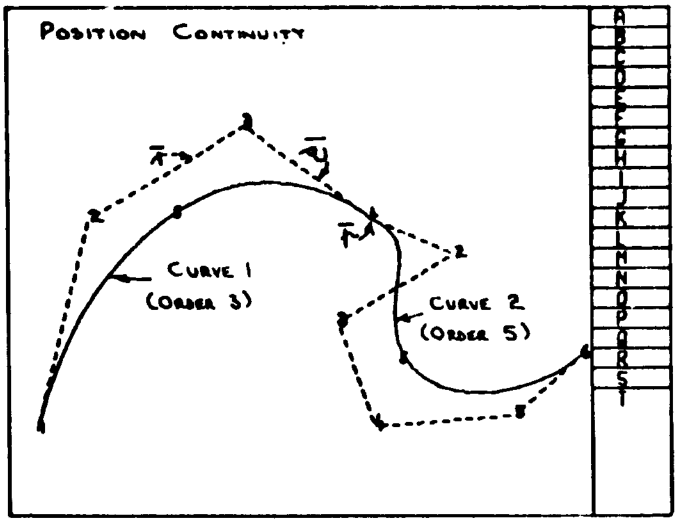


FIG 22 a.. BEZIER CURVES

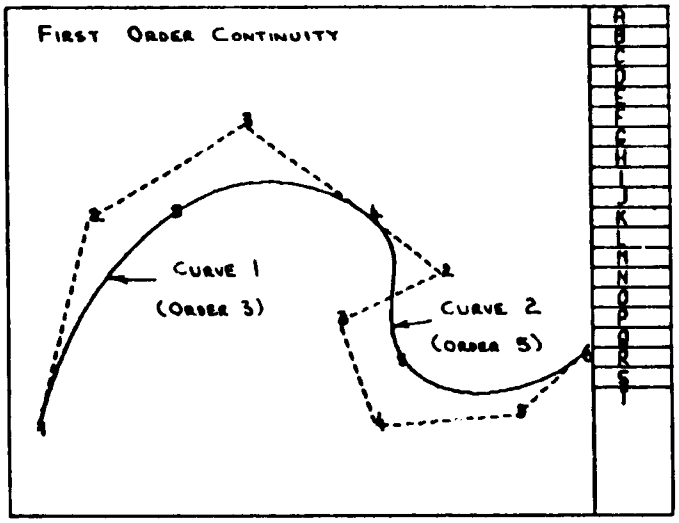


FIG 22. b. BEZIER CURVES

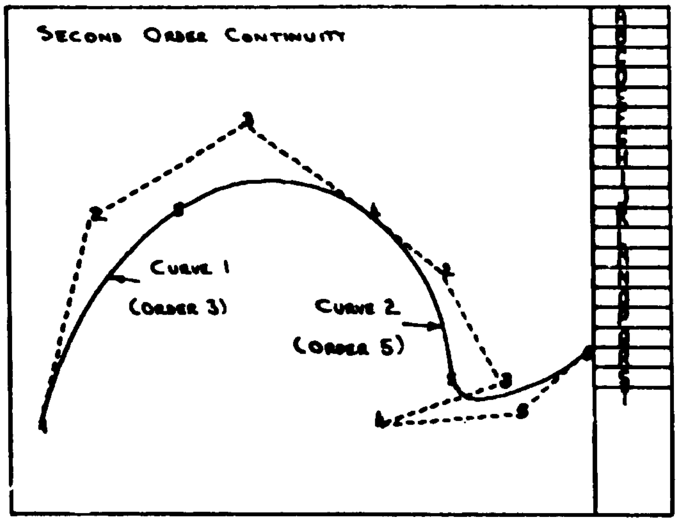


FIG 2.2 C - BEZIER CURVES

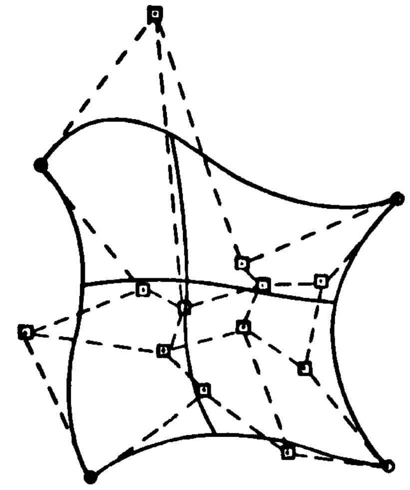
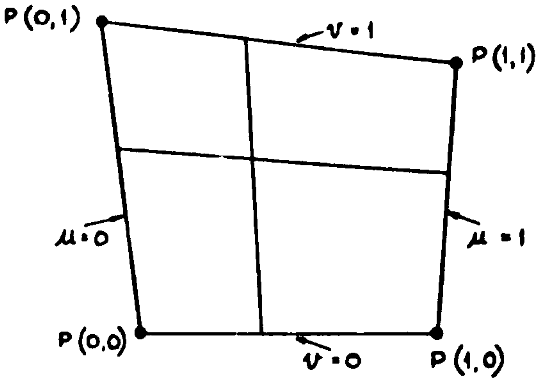


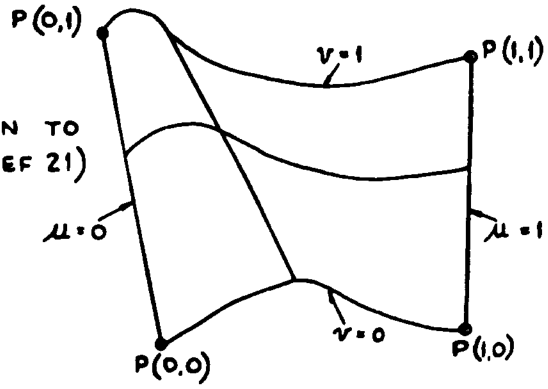
FIG. 23 BICUBIC BEZIER PATCH AND ASSOCIATED POLYGON NET

(corner) points, the slopes of the slant and finish of each boundary curve and twist vectors. The later vectors do not change the position or boundary curve slope at the nodes but allow variations in the Z direction to manipulated in the interior of the patch. Fig (24) These patches can also be joined to form a complete car body shape or that of a ship or aircraft.

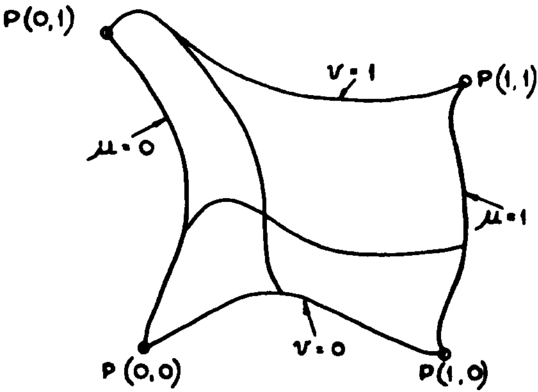
The result of the analysis is to produce a complete description of the surface either in surface parametric form or in XYZ co-ordinates. Manufacture can then proceed by obtaining a parallel surface having an offset equal to the radius of the ball ended cutter and either following the parametric curves or the contour curves after applying that procedure. See Figs (25,26,27)



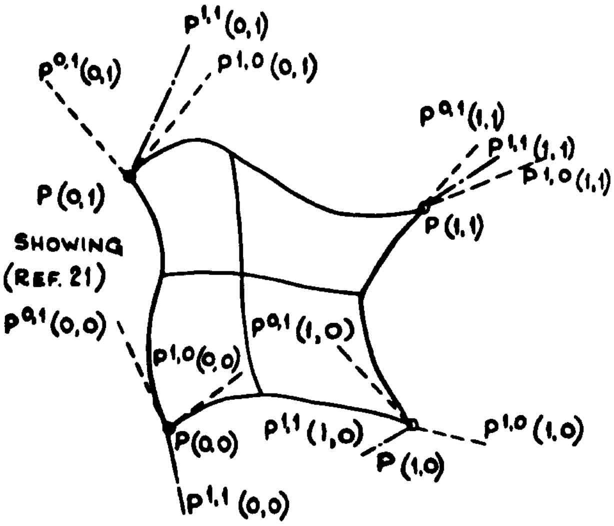
BILINEAR SURFACE
INTERPOLATING FOUR CORNER POINTS (REF.2



BILINEAR INTERPOLATION TO
FIXED v BOUNDARY CURVES (REF 21)



BILINEAR INTERPOLATION TC
FIXED μ AND v BOUNDARY CURVES
BILINEAR COONS SURFACE (REF. 21)



BICUBIC COONS PATCH SHOWING
SLOPE AND TWIST VECTORS (REF. 21)

FIG 24

Coons Surface Which
Has to be Machined

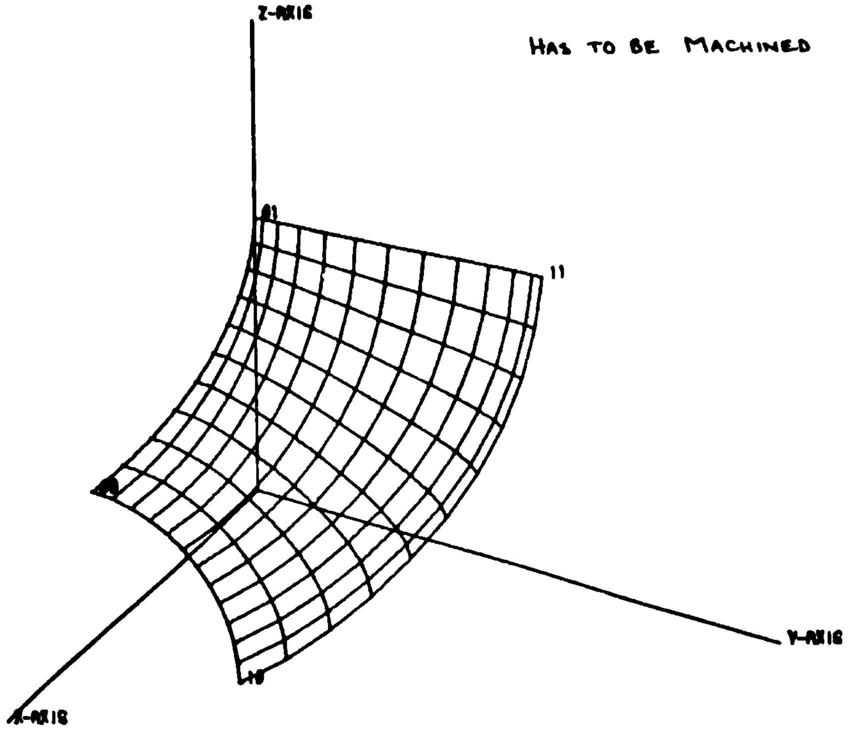
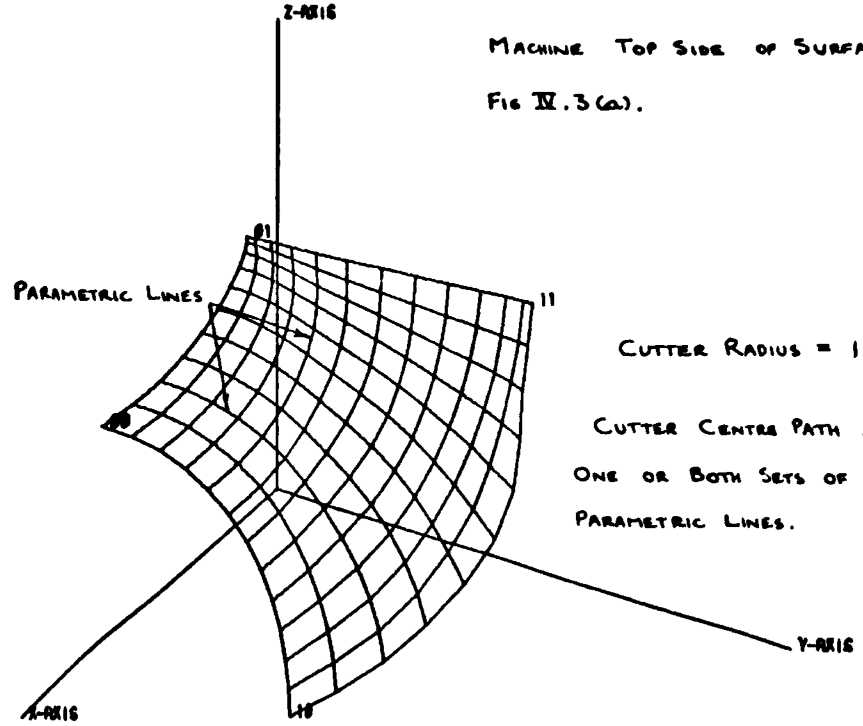


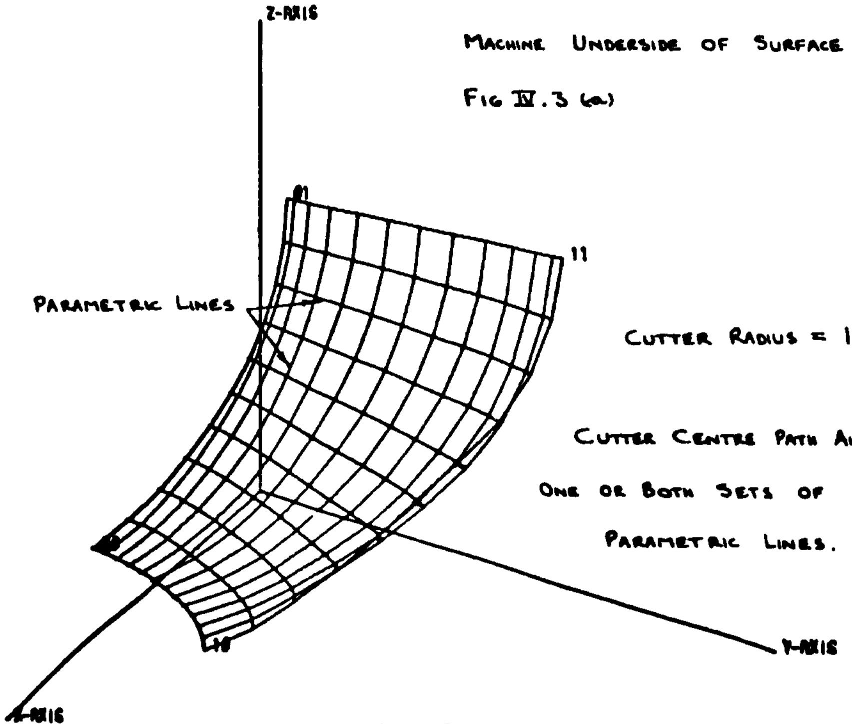
Fig 25



OFFSET COONS SURFACE TO MACHINE TOP SIDE OF SURFACE IN FIG IV.3 (a).

CUTTER RADIUS = 1

CUTTER CENTRE PATH ALONG ONE OR BOTH SETS OF PARAMETRIC LINES.



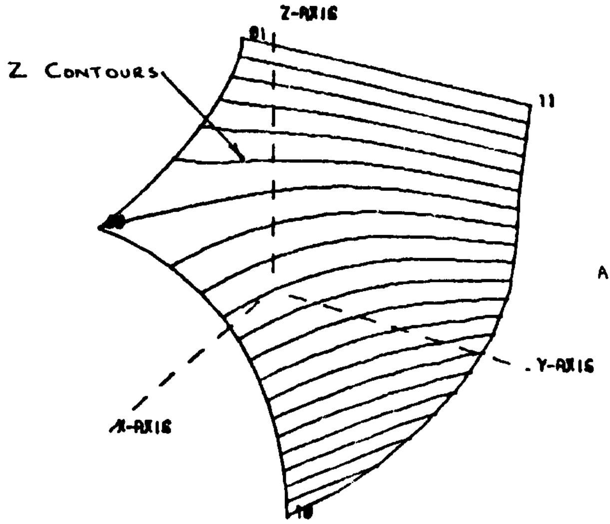
OFFSET COONS SURFACE TO MACHINE UNDERSIDE OF SURFACE IN FIG IV.3 (a)

CUTTER RADIUS = 1

CUTTER CENTRE PATH ALONG ONE OR BOTH SETS OF PARAMETRIC LINES.

FIG 26

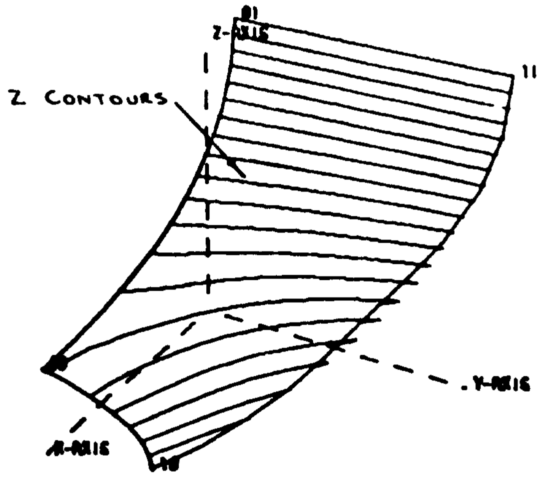
Contours on Offset Coons Surface to Machine Top Side of Surface in Fig IV.3 (a)



Cutter Radius = 1

Cutter Centre Path Along the Contour Lines

Contours on Offset Coons Surface to Machine Underside of Surface in Fig IV.3 (a)



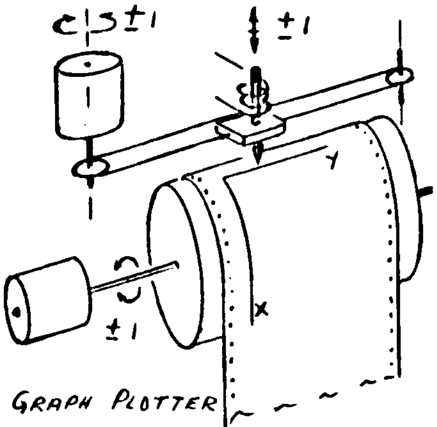
Cutter Radius = 1

Cutter Path Along the Contour Lines

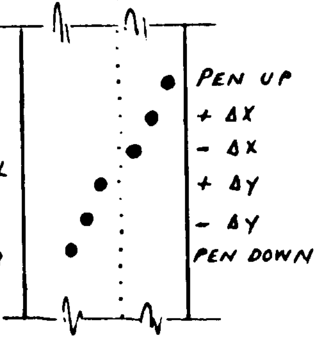
Fig 27

N/C Production Phase

The machine tools are controlled by patterns of digital pulses (machine language). This is most easily seen in the case of a graph plotter. These machines are driven by stepper motors which move a pen by small increments in the X and Y directions, and an induction coil which raises and lowers the pen. One simple electrical pulse is used to control each increment of movement.



GRAPH PLOTTER
FIG 28



CONTROL TAPE
FIG 29

It is extremely tedious for the human operator to control the machine at this level. A higher level language is used to allow a person to operate in a more familiar environment -

e.g. CALL MOVTO2 (X(I) , Y(I))
CALL LINTO2 (X(I) , Y(I)) etc

and a processor employed to convert these statements to trains of pulses to control the operation of the plotter.

In applications where the machine language has a simple form it is expedient to write the processor into the drawing programme or alternatively arrange it as a subroutine which can be called from the drawing programme. Such an approach could be used for machines which cut contours on plain surfaces or plates - AGIECUT machines for example.

However, most engineering components have more complicated forms and the machine tools used to produce them have a variety of control methods and systems. To cope with this, the interface between the machine tool and the human operator is organised usually in two stages.

1) A descriptive language with a translation processor

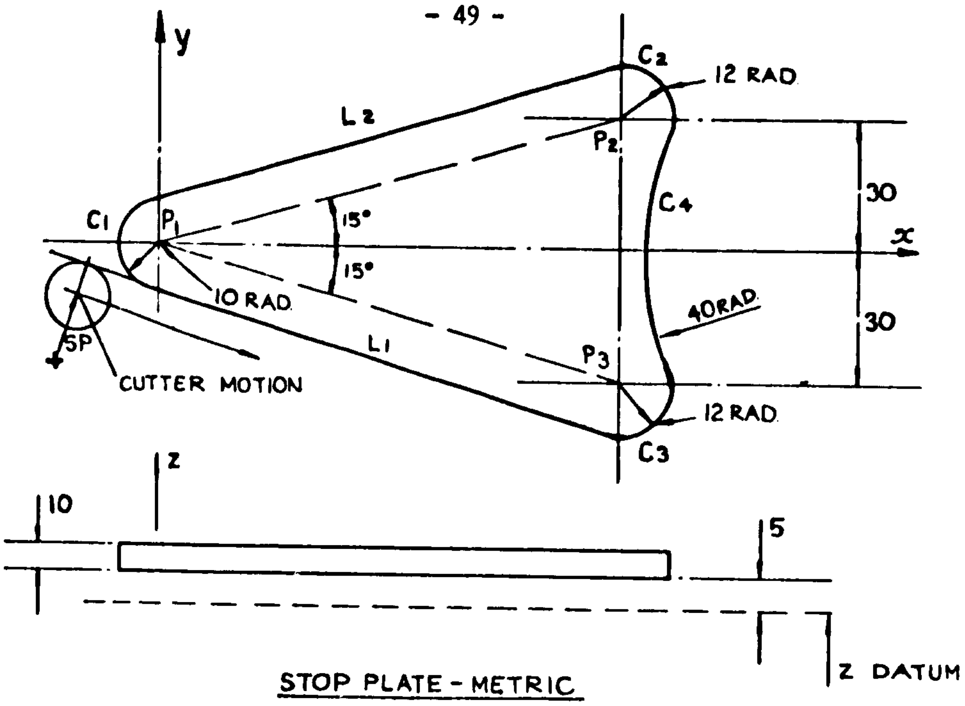
2) A post processor for each type of machine tool.

Part Programme - Stage 1

The operation in Stage 1 is known as part-programming and consists of writing a series of statements about the shape of the component and instructions about the movement of the cutting tool. A number of languages have been developed for this purpose but perhaps the best known is the American package called APT (Automatically Programmed Tools). The form available is the United Kingdom is NELAPT and for 2½ axis milling machines it is 2CL. The continental form is called EXAPT and is used for N/C drilling and boring machines.

The general organisation of the language is best illustrated with reference to a simple example (fig. 30). The language has a FORTRAN flavour and indeed FORTRAN type statements can be included. The programme listing starts with PARTNO with a title heading and terminates with STOP and FINI. In between the statements can be grouped under the following general headings:-

FIG. 30



STOP PLATE - METRIC

```
PART NO              STOP PLATE(DRG. NO. USDDILL1) } Title, start
                                                     of block
REMARK    N/C MACHINE INSTRUCTIONS                 }
          MACHIN/NELMIL                            }
          CUTTER/10                                } N/C machine
          SPINDL/350                               }  instructions
          TOLER/0.01                               }
          FEDRAT/100                               }
REMARK    BASIC DERIVED DIMENSIONS                 } Basic derived
          X 12 = 30/TAN (15.0)                     } dimensions
REMARK    GEOMETRIC STATEMENTS FOLLOW              }
      SP = POINT/-25, -25, 25                      }
      P1 = POINT/0, 0, 5                           }
      P2 = POINT/ X12, 30, 5                       }
      P3 = POINT/ X12, -30, 5                      }
      C1 = CIRCLE/CENTER, P1, RADIUS, 10           } Basic
      C2 = CIRCLE/CENTER, P2, RADIUS, 12           }
      C3 = CIRCLE/CENTER, P3, RADIUS, 12           } geometry
      L1 = LINE/RIGHT, TANTO, C1, RIGHT, TANTO, C3 }
      L2 = LINE/LEFT, TANTO, C1, LEFT, TANTO, C2   }
      C4 = CIRCLE/XLARGE, OUT, C2, OUT, C3, RADIUS 40
      PL = PLANE/P1, P2, P3                        }
REMARK    MOTION STATEMENTS FOLLOW                 }
          FROM /SP                                 }
          GO/TO, L1, TO, PL                        }
          GORGT/L1, TANTO, C3                      }
          GOFWD/C3, TANTO, C4                      } Motion
          GOFWD/C4, TANTO, C2                      }
          GOFWD/C2, TANTO, L2                      } statement
          GOFWD/L2, TANTO, C1                      }
          GOFWD/C1, TANTO, L2                      }
          GOTO/SP                                  }
          STOP                                     } Termination,
          FINI                                     } end of block
```

Machine Instruction

Basic Derived Dimensions

Basic Geometry Dimensions

Contour Definitions

Basic Motion Statements

These statements broadly follow the general format

Symbolic Name = Title / definition

where = and / are reserved symbols which separate the three main parts of each statement.

e.g.

MACHIN/ name of machine

SPINDL/ speed in rpm

PNOI = POINT/ definition

LOI = LINE / definition

CRO = CIRCLE/ definition

PLI = PLANE/ definition

FROM/ position definition

GO/	TO ON PAST	, drive surface	TO ON PAST	, part surface	TO ON PAST	check surface

GOFWD/ definition

GO TO/ definition of location

The language almost explains itself and the documentation is usefully set out as a dictionary of terms and definitions which cover all the normal situations encountered in component shapes in general engineering practice. A few examples extracted from N. E. L. Report No. 543 are illustrated in fig. 31.

POST-PROCESSOR - Stage 2

The complete part-programme is presented to the computer via cards, paper tape, teletype etc. and is put through a processor appropriate to the language used. The part-programme is data for this processor and the output from it consist of

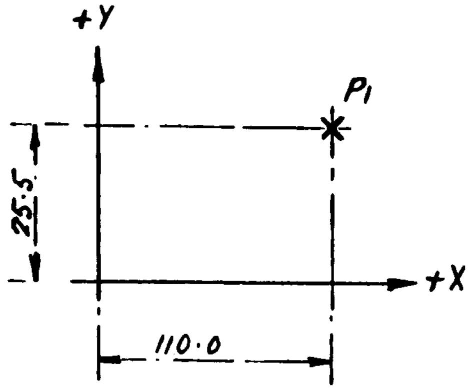
a) co-ordinate values of the ends of all the charge points of the line segments and planes

b) machine control information see fig (32).

The next stage is to convert this information into the control pulses which will control the machine tool. Unfortunately there are a number of different codes for this purpose so that one requires a POST-PROCESSOR for the particular machine tool which is to be used. The output from the final stage is a paper tape (a magnetic tape or by Direct Numerical Control (DNC) from the computer) coded to suit the chosen machine tool. See fig (33). Each block or line consists of a string of alpha numeric coding one example of which has the following format:

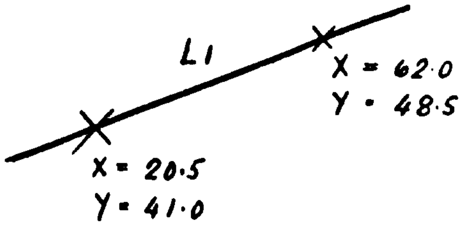
BlocknumberScalefactorDimensionalincrementsFeedrate

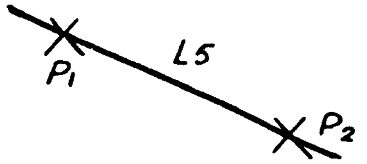
N007G01X-0242Y+0112F081



P1 = POINT/X, Y, Z

P1 = POINT/110., 25.5

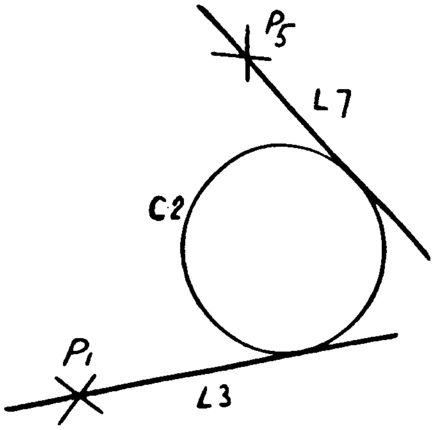




L1 = LINE/X1, Y1, X2, Y2

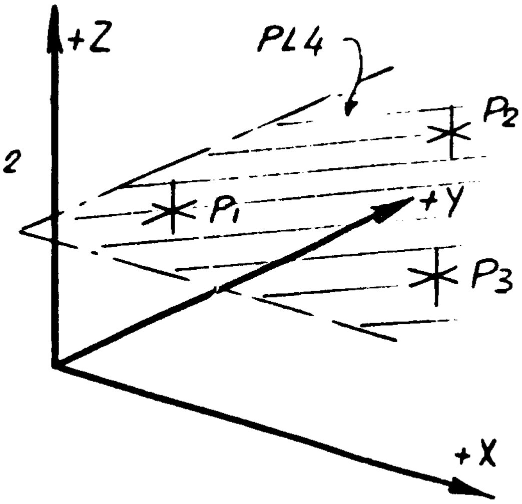
L1 = LINE/20.5, 41.0, 62.0, 48.5

L5 = LINE/P1, P2



L3 = LINE/P1, RIGHT, TANTO, C2

L7 = LINE/P5, LEFT, TANTO, C2



PL4 = PLANE/P1, P2, P3

FIG. 31

SOME BASIC GEOMETRY DEFINITIONS.

```
PLEASE POST TO PROF TOM ALLAN  DEPT

 NELAPT VERSION 009 JUN74..                OFFICIAL NEL 1108 RELEASE (L31)

 2CL - TOOL OFFSETS/CUT VECTORS SECTION 17 SEP 74

 PARTNO PROF T ALLANS DEMO WHEEL NO.2                            PAGE  29

     SEQ.  STAT. CLTAPE
      NO. LABEL  REC.NO.


     162            293   DS IS /
                                    X                Y                 Z
                              -51.5910158      -37.4830608       -53.4899998

     162            294             = CIRCLE / CANON
                                -43.8325    -31.8462       .0000       9.5900

     162            295   DS IS /
                                   X                 Y                  Z
                              -53.1444869      -34.5264616       -53.4899998
                              -53.458 688      -30.7302651       -53.4899998
                              -52.2842526      -27.1065106       -53.4899998
                              -49.8144224      -24.2151642       -53.4899998
                              -46.4017732      -22.5030162       -53.4899998
                              -42.6021185      -22.2346389       -53.4899998
                              -38.9925914      -23.4515033       -53.4899998
                              -36.1309657      -26.9655719       -53.4899998
                              -34.4594398      -29.3883543       -53.4899998
                              -34.2363062      -33.1999394       -53.4899998
                              -35.4960465      -36.7857265       -53.4899998
                              -38.0439978      -39.6172261       -53.4899998
                              -41.4864326      -41.2478943       -53.4899998
                              -45.2914042      -41.4257517       -53.4899998
                              -48.8709426      -40.1233139       -53.4899998
                              -51.591 153      -37.4830604       -53.4899998

     163            296   DS IS /
                                   X                 Y                 Z
                              -51.591 153      -37.4830604         .0000000

     163            297   DS IS /
                                   X                 Y                 Z
                              -46.0241694      -33.4385109         .0000000

     160                  TRACUT /        ///0

                                   .3090        .9511      .0000      .0000
                                  -.9511        .3090      .0000      .0000
                                   .0000        .0000     1.0000      .0000

     162            299   DS IS /
                                   X                 Y                 Z
                               19.7060037      -60.6488757         .0000000

     162            300   DS IS /
```

FIG 32

```
NEL POSTPROCESSOR    PROF ALLAN    DEMO,1


MACHINE 3 SELECTED       PLESSEY  2CL  POST  PROCES


STATEMENT      BLOCK                                                  X           Y

   164     N386G1X-336Y-1718Z+3454F023                           -61.7580    -45.590
           N387G01X-3368Y-1726Z+346F023                          -65.1260    -47.316
   165     N388G1X+8182Y-2658F014                                 16.6940    -73.896
           N389G01X+8182Y-2664F014                                24.8760    -76.560
   166     N39G1X-0596Y+3728Z-3454F023                            16.9160    -39.280
           N391G01X-0596Y+372Z-346F023                            18.3200    -35.560
           N392X-5296Y-2458F021                                   13.0240    -38.018
           N393X-344Y-063F034                                      9.5840    -38.848
   167     N394X-3504Y-0688F034                                    6.0800    -39.536
   168     N395G1X-2358Y-7256F016                                -17.5000   -112.096
           N396G01X-2356Y-7264F016                               -19.8560   -119.360
           N397X+6908Y-0836F017                                  -12.9480   -123.196
           N398X+9684Y-0866F012                                   -3.0640   -121.062
           N399X+9926Y+0156F012                                    6.8620   -120.906
           N4X+9882Y+097F012                                      16.7440   -119.936
           N401X+9768Y+1774F012                                   26.5120   -118.162
           N402X+959Y+2568F012                                    36.1020   -115.594
           N403X+9346Y+3346F012                                   45.4480   -112.248
           N404X+9042Y+41F012                                     54.4900   -108.148
           N405X+8676Y+4826F012                                   63.1660   -103.322
           N406X+825Y+5522F012                                    71.4160    -97.800
           N407X+7772Y+6178F012                                   79.1880    -91.622
   169     N408X+7034Y+673F012                                    86.2220    -84.892
   170     N409G1X-6174Y+4484F016                                 24.4820    -40.052
           N41G01X-6164Y+4494F016                                 18.3180    -35.558
   188     N411G1X+0596Y-3728Z+3454F023                           24.2780    -72.838
           N412G01X+0598Y-3722Z+346F023                           24.8760    -76.560
   189     N413G1X-2262Y+696F016                                   2.2560     -6.960
           N414G01X-2256Y+696F016                                   .0000      -.000
           N415M0
           N416M0
           N417M0
   196     N418M0
           N419M0
   197     N42M0

                                                      ••••••••••••••••••••••••••••••••
                                                      •   4 ERRORS - PAPER TAPE OUTPUT
                                                      ••••••••••••••••••••••••••••••••
```

FIG 33

ORGANIZATION FOR AUTOMATING THE N.C. PROCESS

The writing of a part programme is a time consuming operation and it takes time to carry out the de-bugging operation which is always attendant on manual programming. If a computer programme can be devised which would perform this task, it would be a considerable help towards automating the total process. It is interesting to note the basic difference in outlook at present in the two areas, engineering drawing and N.C. machining. In the former attention is centred on the material, that is, on the solid side of the component boundary, whereas in the latter the object is considered as a collection of cavities and the component is what is left over once the cavities have been formed.

In trying to automate the part programme process, the first stage is to perform an analysis of the forms of cavities encountered in a component or range of components and devise a set of standard forms which will cover this group. A file can then be established for each shape of cavity in the set and a sub part programme written to each file for the appropriate cavity, care being taken to start this and finish at a particular set point. This will ensure that the files can be combined in any order or grouping. (Fig 34)

All that remains is for a master programme to be written for a particular component calling in the appropriate file for the cavities in order. As will be seen later, the master programme can be organized on two files: one written by a program which automatically draws the component, the other organized as an interactive interface to the user. Fig. 35 illustrates the general organization of such a scheme.

FIG. 34

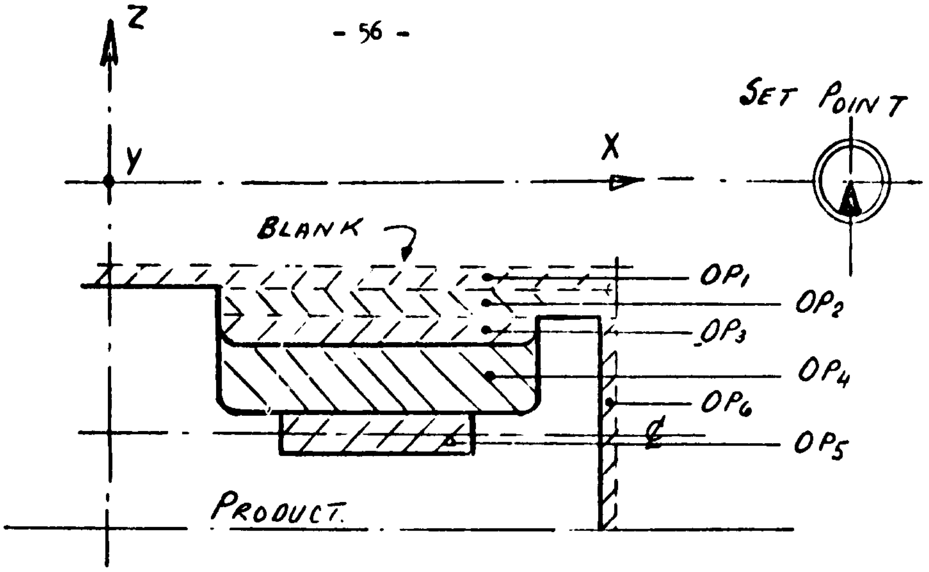
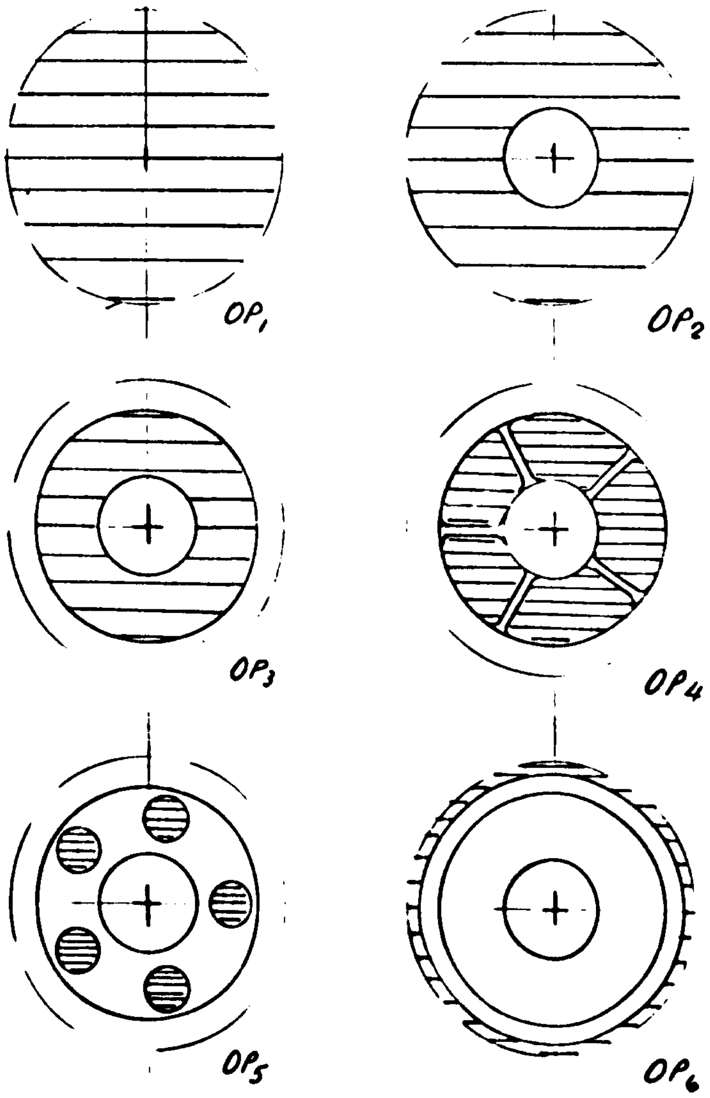

Z
y
X
SET POINT
BLANK
OP1
OP2
OP3
OP4
OP6
OP5
℄
PRODUCT.

FIG. 7


OP1
OP2
OP3
OP4
OP5
OP6

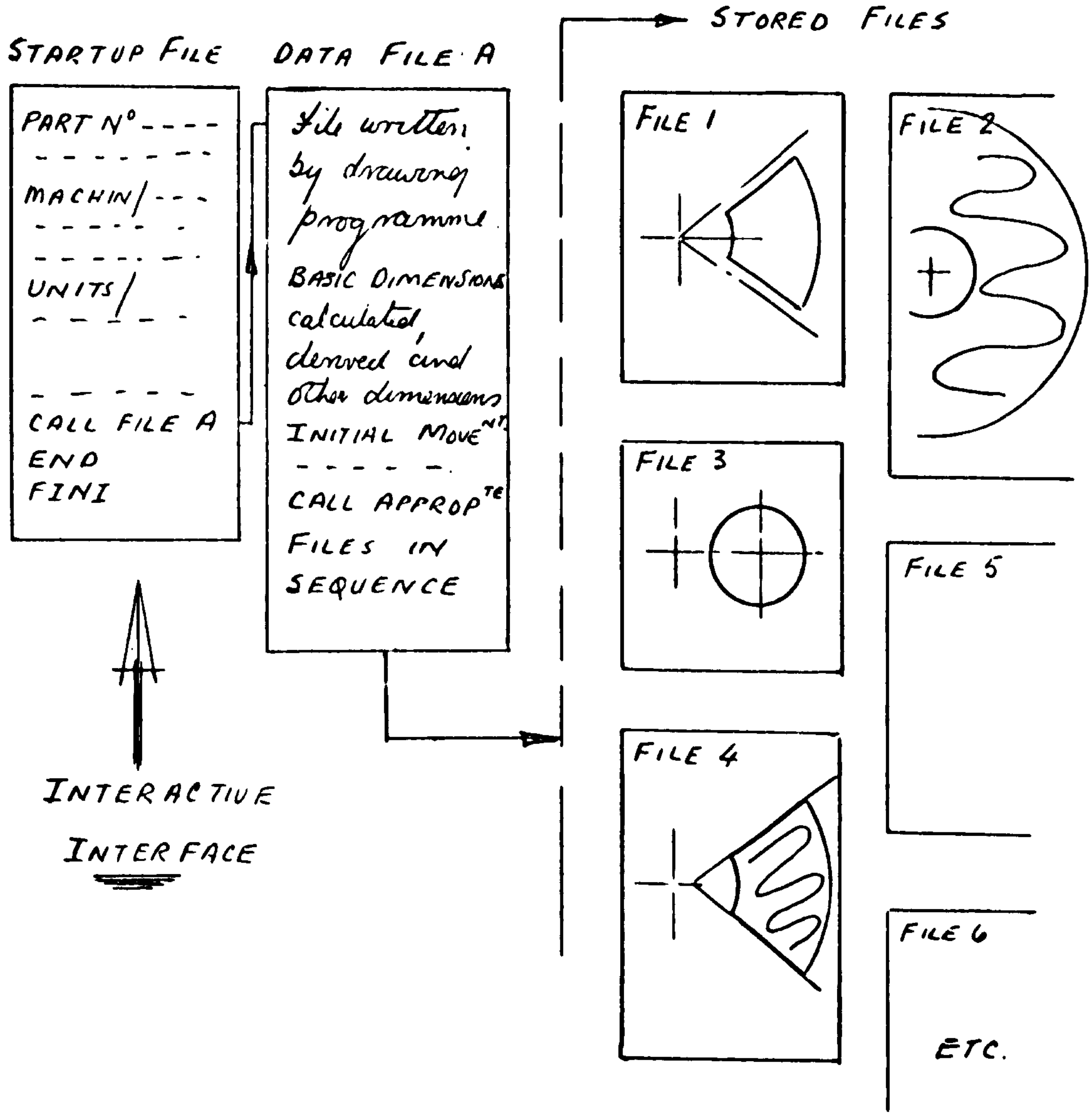

STARTUP FILE
PART N° ----
MACHIN/ ---
UNITS/
CALL FILE A
END
FINI
INTERACTIVE INTERFACE
DATA FILE A
File written by drawing programme.
BASIC DIMENSIONS calculated, derived and other dimensions
INITIAL MOVE^NT
CALL APPROP^TE FILES IN SEQUENCE
STORED FILES
FILE 1
FILE 2
FILE 3
FILE 4
FILE 5
FILE 6
ETC.

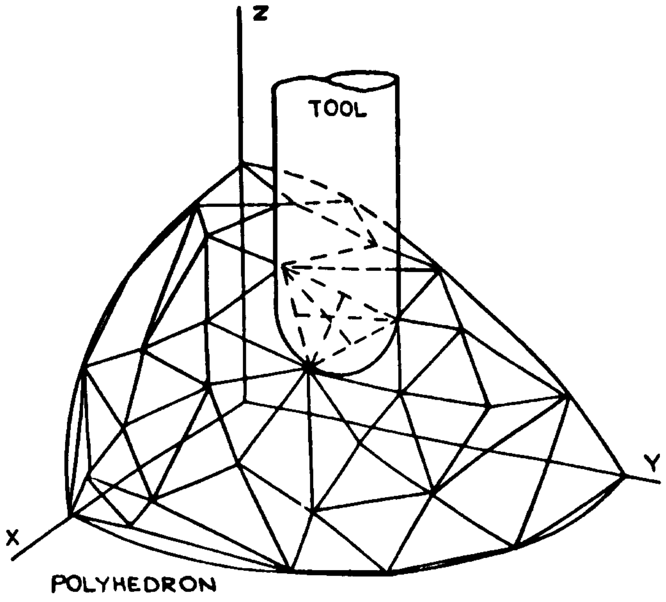
FIG. 35

This would allow a complete part programme to be assembled automatically and subsequently it could then be passed through the stage one processor and hence through the stage two processor from which an N.C. machine control tape could be outputed. This N.C. tape could then be used in the machine which was to cut the component.

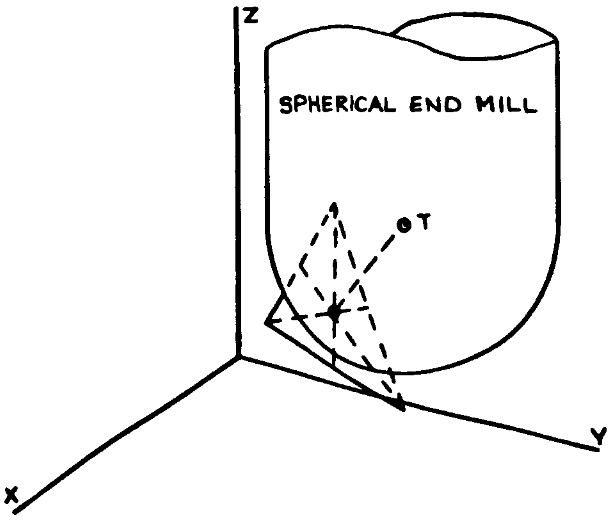
Three Dimensional Surfaces

Most manufacture involves nothing more complicated than a $2\frac{1}{2}$ axis capability. What has been discussed so far is in that area and it is one which has recurred the most attention because of its wide application. Three dimensional surfaces do have to be dealt with. In discussing the graphics phase some techniques for handling surfaces were indicated. Here it was obvious that contours could be produced for the surface which would mean that a $2\frac{1}{2}$ axis machine capability would be adequate. On the other hand multi-axis machines could be used to follow the parametric lines and so produce the surface.

Another interesting technique due to Prof. Duncan from Vancouver is what is known as Polyhedral Machining. Essentially this replaces the surface with a series of triangular facets. A ball ended cutting tool of a certain diameter 'visits' and touches the centre of all the facets it can without invading the others. If in the first pass it has not touched them all a smaller tool is used and some of these facets remaining are machined. This is continued till all facits have been visited and the surface is 'complete'. fig (36).



FACETS OF POLYHEDRON WHICH APPROXIMATES THE DESIRED SURFACE



TOOL IN CONTACT WITH CENTROID (C) OF ONE FACET

FIG 36

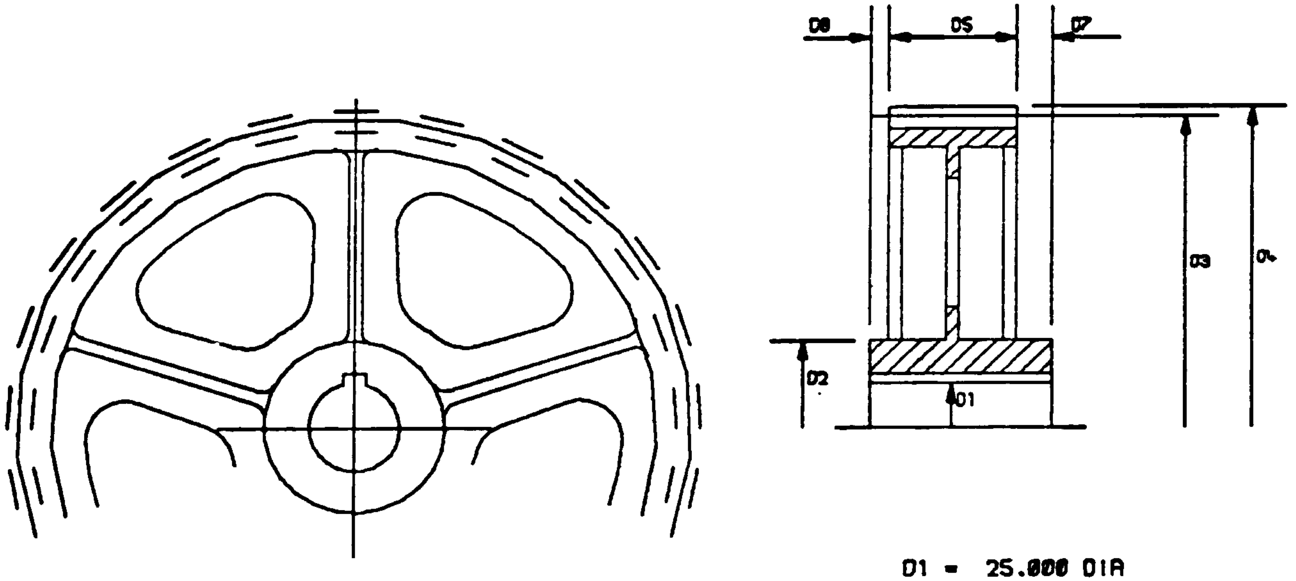
Concepts of Integrated C.A.D. and Manufacture

The use of computers in helping to solve complicated problems of stress and strain, temperatures and pressure or other field problems, helping to keep track of money, or to control machine tools or traffic, is now fairly widespread. Whilst their integrated use is comparatively rare, it does not require a great deal of ingenuity to see how, with existing techniques, some of the programs developed individually for limited objectives could be linked together covering a whole design project.

One concept is to interlink computer programs, files and processors, etc. in an appropriate manner to produce a package which will integrate the analytical, graphical and NC production phases of component design. In order to demonstrate the process and to provide tangible proof of its viability we have prepared an embryo package for the design and manufacture of gear wheel carcasses. This package automatically produces a drawing of the component (fig 37) and a machine tape to enable the carcasses to be automatically cut from a blank disc. Plates I & II The organisation of the system is illustrated in fig (38) and is essentially an interactive process in which the designer can implement whichever decision he may feel appropriate. While this system can be used in its complete form, each of the sections can be accessed separately or used in a semi-manual manner.

An alternative approach to using existing languages and processors

** DRAWING FOR SPUR GEAR WHEEL **



62 TEETH .. 3.00 MODULE

D1 = 25.000 DIA
D2 = 50.000 DIA
D3 = 186.000 DIA
D4 = 192.000 DIA
D5 = 35.000
D6 = 5.000
D7 = 10.000

* DESIGN DEPT. * UNIVERSITY OF STRATHCLYDE *

FIG. 37

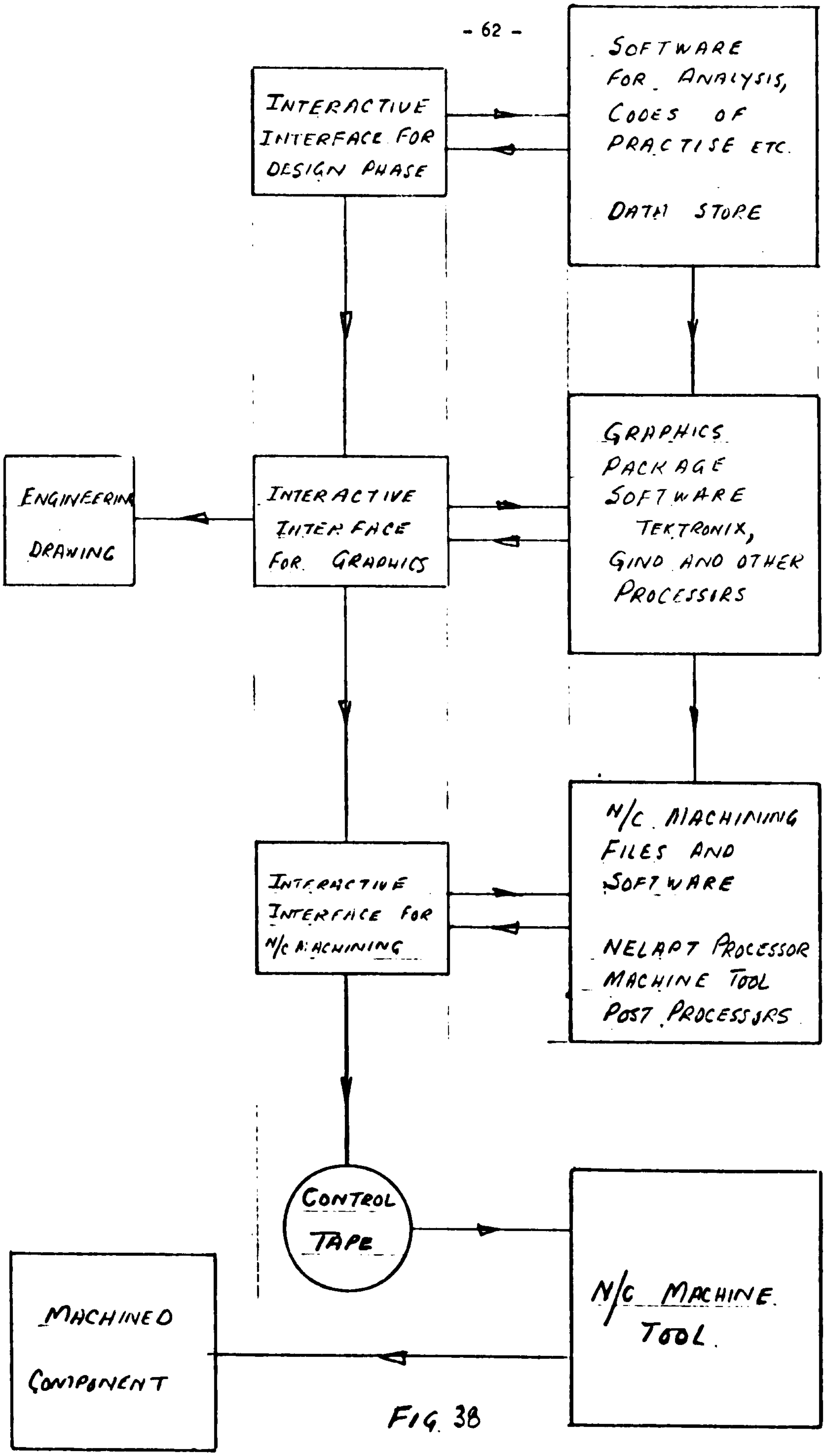

INTERACTIVE INTERFACE FOR DESIGN PHASE
SOFTWARE FOR ANALYSIS, CODES OF PRACTISE ETC.
DATA STORE
ENGINEERING DRAWING
INTERACTIVE INTERFACE FOR GRAPHICS
GRAPHICS PACKAGE SOFTWARE TEKTRONIX, GINO AND OTHER PROCESSORS
INTERACTIVE INTERFACE FOR N/C MACHINING
N/C MACHINING FILES AND SOFTWARE
NELAPT PROCESSOR MACHINE TOOL POST PROCESSORS
CONTROL TAPE
N/C MACHINE TOOL
MACHINED COMPONENT

FIG. 38

which have been developed independently for different applications to form a unified system, it is probably more logical to devise a new single language and compiler which can handle all three phases of this integrated approach. Such languages are liable to be developed in the future. One such attempt in this direction which is likely to be announced towards the end of this year is known as 'AD 2000'. It has been developed by Manufacturing and Consulting Services Incorporated of California and effectively compiles the graphical and NC manufacturing elements under a common language and data structure. Such developments will go a long way to ease the problem of integrating different aspects of technology to suit future needs.

CONCLUSION

Countless millions of man hours have been spent in developing computer techniques which can be used in all aspects of industrial society. No doubt development will continue in these and other areas in the future. At the present time, however, there is a considerable gap between what is potentially available and what is being usefully employed. For a comparatively small investment the present situation can be fairly easily assimilated and with a little ingenuity can be turned to the benefit of any community, even with its own peculiar industrial problems and limitations. The purpose of this paper has been to give some idea of the range and scope of the available techniques at the present time.

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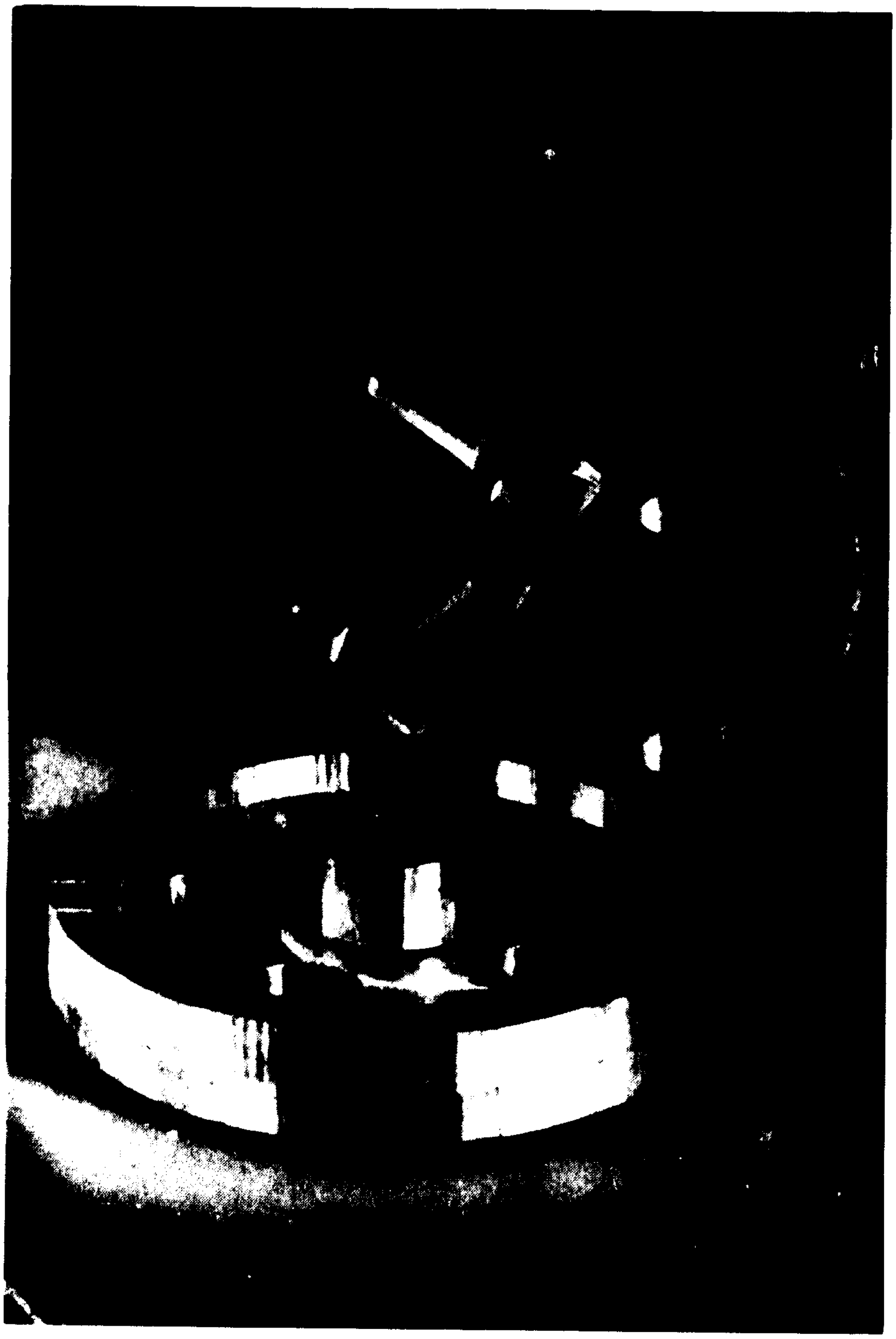
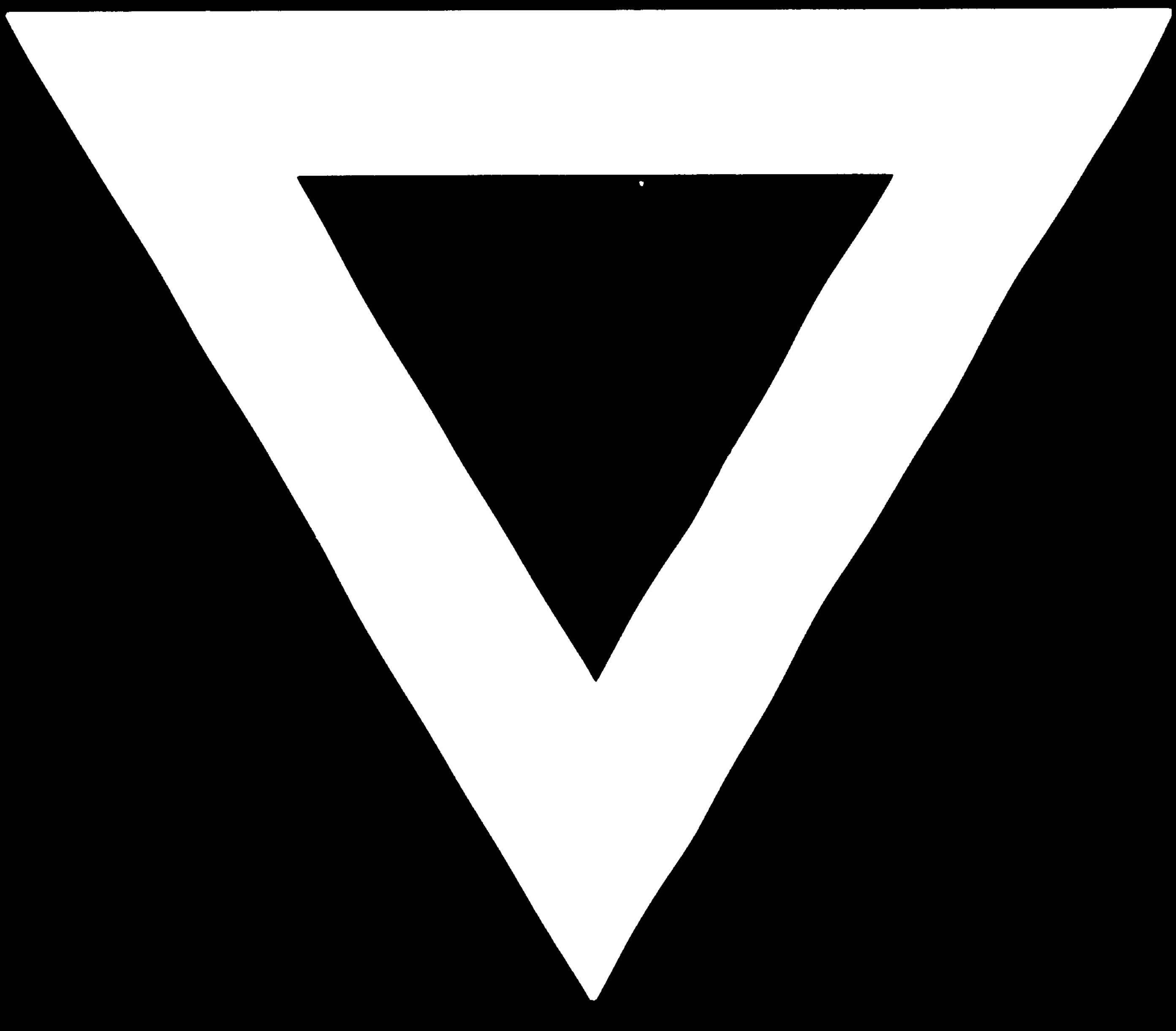


PLATE I - MACHINED CARCASE OF WHEELS

PLATE II - ONE STAGE IN THE N/C MACHINING OPERATION

C-672



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