Operating efficiency increases with the processing power of a computer, and therefore there is a continuous market demand for larger computers. Meeting this demand poses difficult design problems for the computer manufacturer which can be solved most efficiently by using automation techniques. In this article, the author describes the automation techniques employed in the design and manufacture of International Computers Ltd.'s 1906A computer.

Automation of the design and manufacture of a large digital computer

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IT IS GENERALLY true that the greater the processing power of a computer, the greater its efficiency in terms of cost per computation (assuming that the formidable problems of feeding a large computer with an adequate flow of work are successfully dealt with).

In addition, as experience and confidence in computing have grown, there has been an insistent demand for the solution of single problems which, while being too large for computers currently in use, could not successfully be partitioned into a number of smaller problems.

As a consequence, there has arisen a continuous requirement from the market for central processors which are both fast and large. The 1906A computer specification was a response to such a demand.

The ICL 1906A specification posed some particularly difficult design problems. In order to meet the fast instruction execution times called for, it was necessary to develop, in collaboration with an American semiconductor company, a family of integrated logic circuits with a typical stage delay of 2ns, which was, in itself, an important exercise in international technical collaboration.

The complexity of the specification involved the connecting together of 40000 of these fast logic gates by 250000 connecting wires. Since the speed of propagation of electrical signals in an insulated wire is only about 1ft in 2ns, the intrinsic speed of the circuits can only be utilised if the average length of the connecting wires is kept to a few inches. In spite of the fact that the central-processor cabinet measures 6ft 4in high by 3ft 8in wide by 27in long and its 800 cableforms contain 11 miles of coaxial cabling and 17 miles of 'twisted-pair' cabling, critical lengths of logic-interconnection wire have been kept down, on average, to a length of 3in (equivalent to a delay of only 0·5ns).

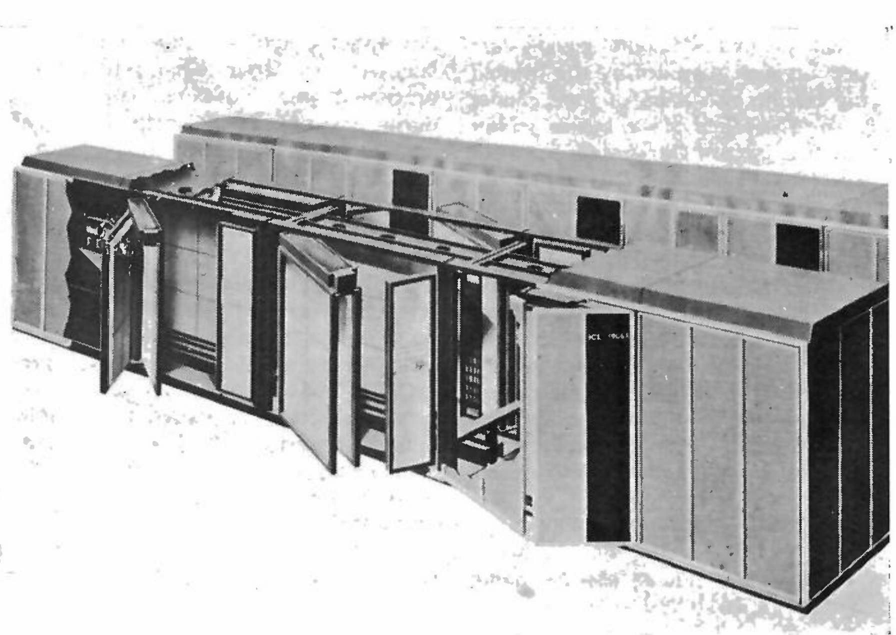
Furthermore, in order to avoid losing time in the interconnections because of multiple reflections travelling back and forth along the wires ('ringing'), all interconnections had to be made in the form of correctly terminated transmission lines of constant impedance. This requirement involved the development of a multilayer interconnection plane ('12-layer platter'), combining stripline techniques with a density of interconnection not hitherto attempted anywhere in commercial equipment.

The degree of precision and mass of data required in the manufacture of these multilayer interconnection platters demanded, in turn, the use of automatic artwork generators, numerically controlled drilling machines and automatic testing machines. The input to all these numerically controlled machines takes the form of punched paper tape or magnetic tape produced by the design-automation system.

The problem of designing and building these multilayer interconnection planes has demanded a major effort, not only in computer-aided design but also in process technology allied to precision engineering.

The design-automation system has been developed as a means of turning the designer's pencil sketches of the detailed logic of a computer into complete manufacturing information and documentation.

A suite of simulation programs called SIMBOL is used first to check the consistency



1 Cutaway view of 1906A computer, showing the logic circuits housed in the swinging door frames

This article is based on a lecture given by C. D. Marsh, G. Haley and G. Adshead to the IEE at Savoy Place on the 13th March 1970.

of the basic overall system design and to allow it to be subdivided into smaller units that can each be handled by separate logic-design teams.

The design-automation suite of programs then operates at the detailed logic level, checking that the circuit-loading rules have not been transgressed and that the logic chains are complete. The programs are used to work out the optimum physical location for each logic element on the interconnection platters, after which the positions of the wiring runs are developed. When this latter phase is complete, the manufacturing information can be produced. This output takes the form of punched paper tapes to drive the artwork generator, the numerically controlled drills and automatic tester, and the line-printer output to provide documentation for production, test and maintenance users.

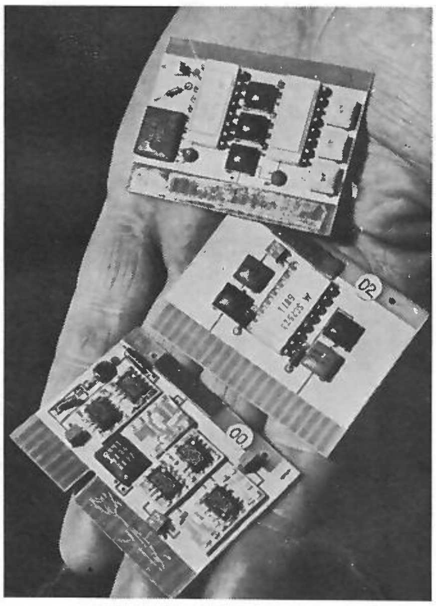
The system keeps an accurate control over the vast amount of data generated in the course of the design process, and has many built-in checking procedures that allow the computer to warn the designer of errors and omissions in his basic work. Once these errors have been corrected, the computer can manipulate the data to develop the physical basis for the design in a rapid and error-free manner. This job is too time consuming and complex for human beings to carry out successfully on such a large scale as is required for this computer.

Hardware system

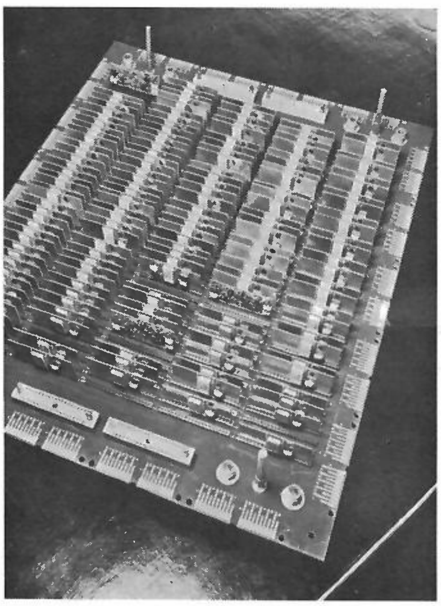
Fig. 1 shows the 1906A computer. Three bays house the logic circuits in the swinging door frames, while the cabinets at each end provide cooling and filtration for the closed-circuit air-conditioning system. The row of cabinets at the rear houses the power-supply system. The memory system, which is not shown, occupies a third cabinet.

The integrated circuits used are a special type of emitter-coupled logic (e.c.l.) on single silicon chips, with up to 100 components (30 transistors, plus diodes and resistors) per chip. The 2 × 1·5 in plug-in modules, of which there are seven basic types (Fig. 2), carry the integrated circuits together with the thick-film multiple-line-matching resistors. Certain nonstandard functions, e.g. for voltage-level conversion at interfaces, are made by hybrid techniques using a multiple-transistor flatpack and thick-film resistors (shown unencapsulated in Fig. 2).

20000 of these circuit modules are conceptually plugged into a continuous multilayer interconnection plane 140 ft². in area. In practice, the largest plane which can conveniently be made is 13 × 16 in—large enough to carry 200 circuit modules, of which 94 (Fig. 3) are used in the computer. These planes are called 'platters' and are connected together (six or nine at a time) along their peripheries to form a larger plane by bridging connectors clamped on to the gold-plated pad areas. Signals between door planes are carried by cableforms of coaxial cable or twisted pairs. The complete machine uses over 800 cableforms, nearly half of which are used for engineer's monitoring purposes.



2 Unencapsulated integrated-circuit modules using special Motorola e.c.l. on single silicon chips



3 12-layer platter loaded with circuit modules

Inside the platters, the signals are carried between modules by the printed wiring on the two pairs of logic planes (Fig. 4). These planes are buried within the platter, accurately spaced from an earth plane to give a 75 Ω-impedance transmission-line characteristic. An orthogonal system is used. X and Y tracks are connected by 0·013 in-diameter holes drilled in 0·030 in-diameter pads and through-hole copper plated. These connections are called 'via' holes. The plane carries about 1000 connections and requires 6500 accurately drilled holes. The X wires are 0·007 in wide and the Y wires are 0·010 in wide. (Spacing from the earth plane is 0·012 in for the X wires and 0·021 for the Y wires.)

Fig. 5 shows a cross-section of a bonded 12-layer board showing the via holes. On the left is a module pinhole going right through the board. The two outer layers merely contain pads for soldering the module connectors. The centre four layers carry various power supplies, which are isolated from the module except when it is desired to make a connection to a power rail. On either side of the power layers are two groups of signal planes. Each group contains an earth plane for impedance matching and an XY pair to carry the logic signals. Some X and Y tracks are shown together with some internal via holes.

Artwork

It will now be useful to present a broad picture of the production processes involved in making the multilayer interconnection platters.

The patterns to be etched on the various copper layers of the platters must be transferred from photographic negatives, known as 'artwork'.

High-accuracy artwork is produced by a precision XY plotter. This XY plotter has a moving light source, controlled nominally to within ±0·001 in over the bed from a magnetic or punched tape. The light beam, controllable in width and intensity by program, plots the artwork at full scale. In practice, most artwork consists of a standard pattern plus a variable part. To save plotting time (and expense!), the film is pre-exposed with the standard pattern and only the variable additions are plotted. The variable parts of each platter design need 0·25 million characters of paper-tape input to the plotter.

All process stages involving the generation or use of artwork must be carried out in a dust-free environment controlled to within 50 ± 5% relative humidity and 70 ± 2°C temperature.

Before applying the artwork to the copperclad laminates, the latter have to be coated with a light-sensitive coating known as photoresist. Most printed-circuit production units use the wet application process, but, for the finest-tolerance work on the logic layers, a dry-film method has proved to be essential to eliminate pinholes and blemishes.

Layup of platter

Although there are 12 etched copper layers in the platter (Fig. 6), they are assembled from seven laminates (five double-sided and two single-sided). The laminates are separated by spacers impregnated with half-cured epoxy resin during assembly in the accurately tooled laminating jig. The assembled layers are heated to 165°C under a pressure of 300 lbf/in² in a steam-heated bonding press to cure the epoxy resin and bond the laminates (Fig. 6).

The 5000 major via holes linking the layers together are drilled (after bonding) on a 16-spindle numerically controlled drill, which has a nominal accuracy within ±0·002 in.

In total, for each platter, 18000 holes must be drilled in glass-fibre laminate to an accuracy of within 0·002–0·003 in. The 6500 via holes in each logic layer have to be drilled before bonding. Drill wear is a major problem and drill consumption is 650 per week.

At various stages during manufacture, it is necessary to test the layers, and a machine has been specially developed to do this automatically. Controlled by punched paper tape, this machine checks for open- and short-circuit conditions between all possible pairs of points, and prints out the location of any errors found. The printed-error slip is attached to any faulty work and sent to the rectification section.

During the development of the foregoing production techniques, many difficult technical problems have had to be overcome. In particular, one can note the almost incompatible nature of many of the processes, as the two following examples show: artwork generation and handling demand a closely controlled dust-free environment, while the associated stages of drilling and sanding generate a great deal of dust, swarf and fibres; accurate registration of the layers demands physical stability of the basic laminates, but these are subject to a succession of wet and dry chemical processes, culminating in an extremely brutal bonding process. The investment in plant and equipment to carry out these tasks has totalled £0·75 million over three years.

Computer-aided-design process

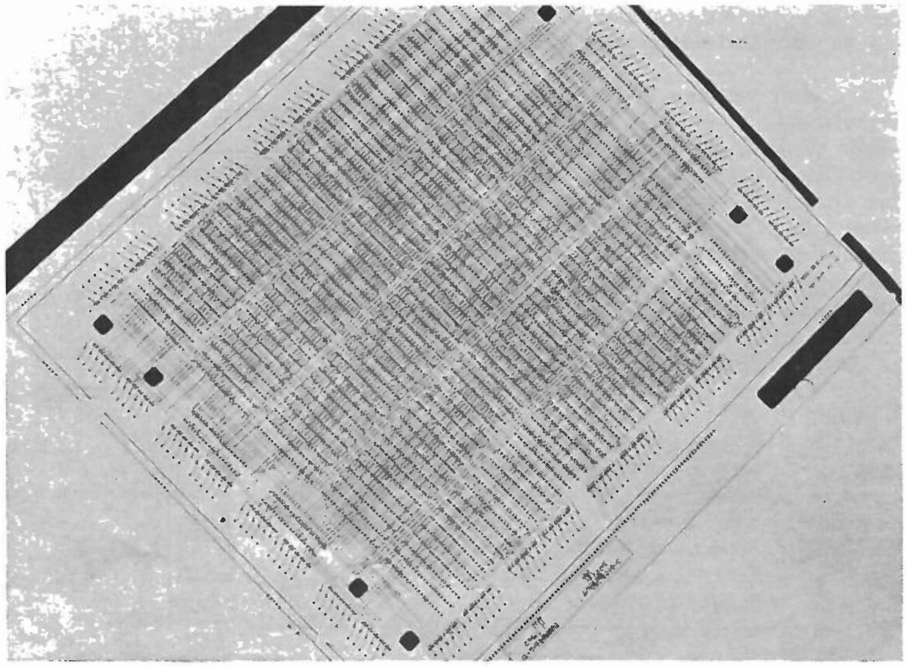
The first main process of design involves breaking down the planning specification into a system structure (Fig. 7). This means defining a set of blocks of manageable proportions (such as a floating-point-unit, store control), each block being made the responsibility of a group of logic designers, who go on to construct the inner details of the logic connections.

The computer-aided design falls into two broad categories. First, the simulation language SIMBOL is used to specify the system structure and order code and to simulate real programs. This operation is to prove that the system structure is viable and that the detailed logic of each block agrees with its system specification.

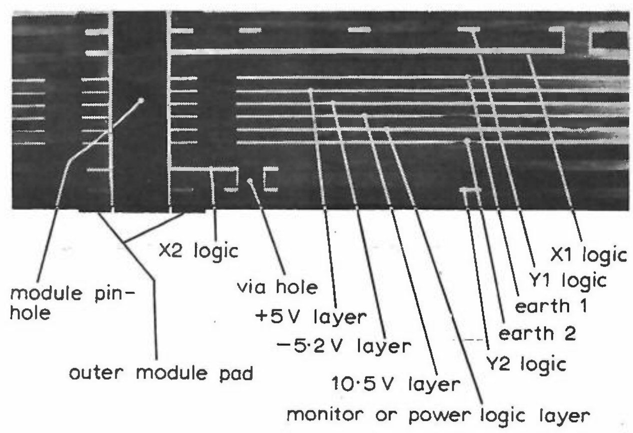
Secondly, the other group of programs forms a design-automation suite known as SYSTEM.67. This suite is concerned with the problem of converting detailed logic into a physical form, deriving the interconnection patterns and generating all the relevant production-information documentation. An 'information expansion' is associated with the process. In this case, a product specification of 10000 characters of information is expanded into 200million characters of production information.

Once the logic engineer has completed his system-design studies with the aid of the simulation program, he is left with a specification of a group of logic. This logic group could be, for example, a floating-point unit occupying nine platters. Ultimately, this group will be defined in detail on 80 sheets of logic drawings.

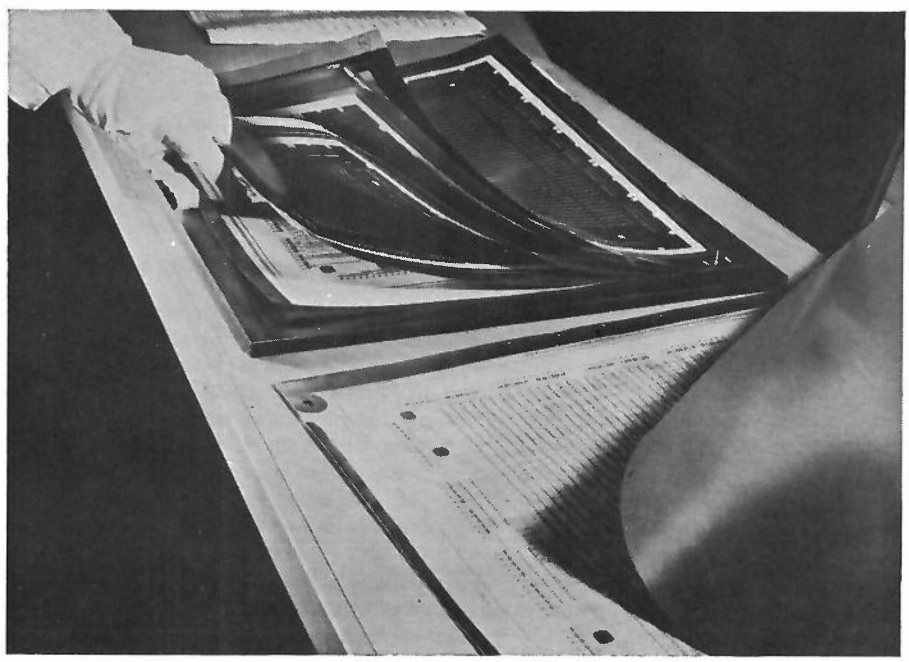
The logic designer roughly sketches out the basic logic. This sketch is then passed to a technical clerk who codes the logical information into the computer input language. This information is then punched on paper tape and fed into the computer. Alternatively, the logic designer may describe his logic in the form of Boolean equations without drawing a logic sketch. Where there are repeated slices of logic, various MACRO facilities



4 Pair of logic layers for carrying signals between modules inside the platter



5 Cross-section of a bonded 12–layer board showing the 'via' holes



6 Lay-up of a platter

may be stored in the computer and called up as requested to minimise the data input.

The main elements of the system are represented in Fig. 8. All information is input to the logic files in the form of modifications. Even brand-new drawings are considered as a modification to an empty file. This is a very fundamental point; it ensures that all possible ramifications of any change are considered. Documentation is always kept in step, and any errors are indicated at the time of the modification.

The engineer can ask for about 40 different types of information printout from the files. Perhaps the most useful printout is the error listing, which lists errors or inconsistencies in the design discovered by the computer's checking routines. If the designer has broken the rules, he soon knows about it! These computer programs can detect over 30 different classes of logic error that may exist on the file.

One of the major design processes is 'placement', or the problem of deciding the location of the logic elements throughout the computer. Each logic element must be associated with a particular circuit on a particular plug-in module on a particular platter.

Basic choice

The basic partitioning choice of which groups of elements are to go on which platter is made by the logic designer; thereafter the computer takes over. The computer program then considers 500–600 elements at a time, and collects together groups of similar elements that can form one plug-in module. This grouping is achieved by scanning round the logic diagrams for similar elements that have been drawn close together and finding the most interconnected clusters.

An interconnection matrix is then set up, storing the links between the modules that are candidates for the 200 module positions. Several cycles of various algorithms involving such manipulative techniques as 'elastic contraction' and 'pair swopping' are used, and eventually a fairly good layout of modules is achieved.

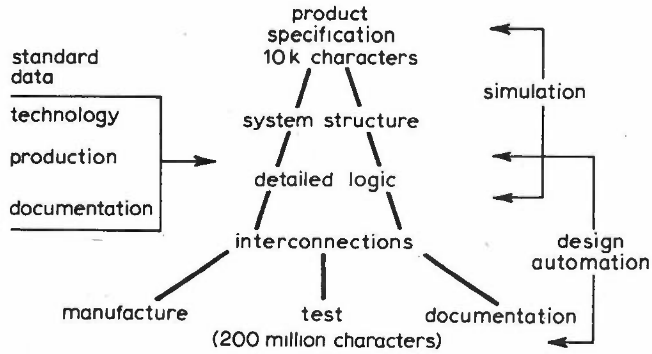
Once the physical placement is complete, the interconnection paths can be developed; this is called 'tracking'. The tracking operation is the job of fitting up to 2000 wires into the two logic layers of the multilayer board. An exhaustive 'maze-running' technique is employed (based on Lee's algorithm), which will only reject a wire if neither plane can possibly accommodate it. In most cases, only a few wires cannot be accommodated, and these are added as hand wires in the final production stages.

From the production file, a large quantity of numerical-control tape is generated to drive the XY plotters, drilling machines and platter tester, and also to generate assembly- and production-control documentation is printed.

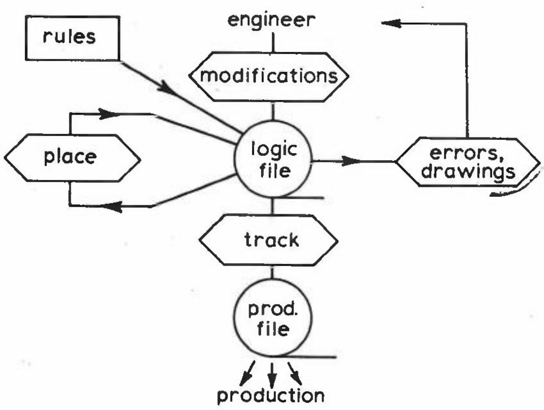
Throughout, all the files store information in a form which preserves previous history. Consequently, any drawing or document may be reproduced as it existed in the past, and, more importantly, the changes to any document between any two dates in the past may be deduced and printed out when required.

A graph plotter attached to the computer draws the finalised logic diagrams directly from the computer files (Fig. 9). The drawing produced is used by the designer as a record of his work, and also by the systems test and maintenance engineers. The diagrams give an accurate picture of the version of the computer that is actually being built. Each week about 200 high-grade master drawings and 300 design copies are produced.

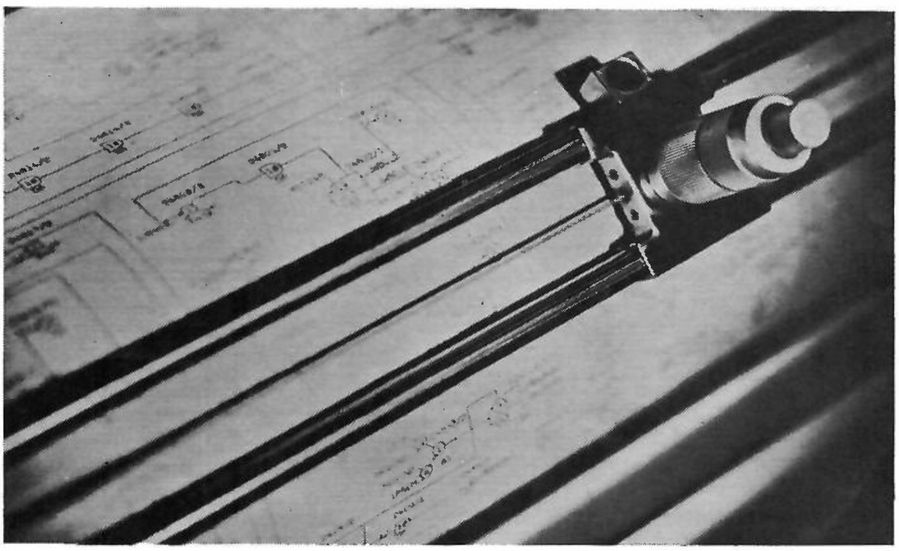
During the course of various operations, the programs need to refer to hardware constants such as dimensions, pin numbers of modules etc. All these data, which are fixed for a particular project, are kept on sets of tables. Each file has a hardware code definition which allows the programs to refer to the relevant tables. To date, over ten types of hardware models using completely different technologies have been constructed using the same set of programs. These programs total nearly 0·5 million instructions which are held, together with the tables, in an overlay structure on disc or drum memories.



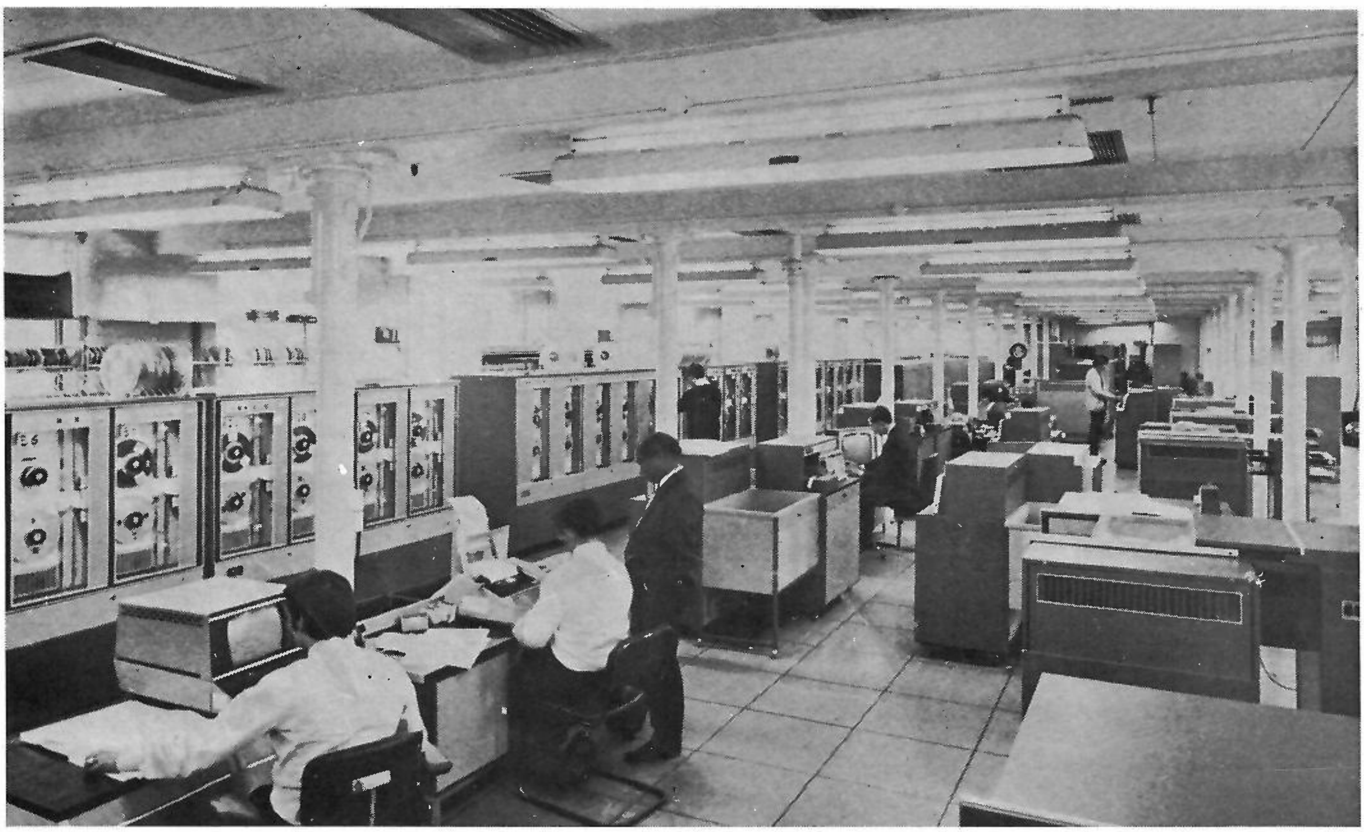
7 Design process



8 Design-automation system



9 Calcomp plotter drawing a logic diagram online from a computer



10 Computer operations room

About half this total of instructions (200000) was needed for the design of the particular machine under discussion. The running of these programs is controlled by a special operating system allowing mixed batch processing and online operation.

Design operations room

The design of each platter, together with the issue of all production information, takes about 20h of computer time. In addition, there is the simulation load, other projects and program development to consider; a complex of three large compatible processors with suitable peripherals is dedicated to c.a.d. problems, and 4000 reels of tape are in use. The total capital investment in design automation at this location is about £1 million.

These machines are run 24h a day on a 3-shift basis. Great emphasis is placed on reducing turn-round time, and very few jobs take longer than 24h. Any design engineer handing in a new logic sketch at, say, 4 p.m. would expect full feedback first thing next morning. Some of the coding and data-preparation operations are performed on the evening shift, and the jobs are run on the night shifts. At present, an online job-control system is used to keep track of over 1000 jobs a week. In this context, a 'job' consumes between 3min and 2h of computer time.

The design-automation department has a staff of about 50, and half of these are involved in the operating, data-control, data-preparation and coding areas. The remainder are engineer/programmers involved in generating new programs and improving the current ones.

It is difficult to define the programming development effort because there is a world of difference between producing the first programs capable of designing a platter and producing a working program suite consuming hundreds of hours a week of computer time. In many problem areas, it is difficult to say where the engineering leaves off and the programming starts. The current library of programs of 0·5million instructions represents the writing of about 40–50 instructions per man per day over the last four years; but the general development goes back over seven years or more.

One aspect of the system described can be called its 'amplification ratio'. For most areas of the machine, about 200 characters of output are generated for each design character input by the design engineer. Where there were large repeated slices of logic, this ratio has reached as high as 7000 : 1.

Benefits from automation

Accuracy of design information is of particular importance in a digital computer. The logic paths are so complex that a large computer never operates twice under exactly the same conditions. In the past, minor errors in wiring in even a small computer have not shown up during months of rigorous testing, but have come to light after a year or more of operation at a customer's site, when a particular combination of input data and program steps has occurred.

Consequently, it is of fundamental importance to check the logic design thoroughly. When one bears in mind that the design information of the 1906A amounts to 200 million characters, it will be realised that manual methods of checking and data transcription could not be contemplated.

The use of a computer simulation technique, followed by a computer check-out of the detailed logic design, reduces the possibility of an undetected design error to a negligible value.

Owing to the complexities of a computer, changes in the logic design are inevitable as development proceeds. It is important to be able to process design changes quickly and generate new manufacturing information and its attendant documentation simultaneously; and this has been one of the prime aims in the development.

Manufacturing-technique accuracy

The importance of generating and maintaining error-free design information has been stressed earlier. It is equally important to ensure that the computer is built exactly to the design information. Wrongly placed wires have been a costly hazard in computer manufacture for many years, but, with the high frequencies involved in nanosecond pulses, the length, positioning and screening of the wires are equally important.

An automated method of manufacture ensures that each computer built is not only interconnected correctly, but that it is exactly identical to the prototype in the important minor details of wire length and positioning. This fact, when coupled with the rigorous pretesting of the plug-in circuit modules, leads to a short and predictable system commissioning cycle. The benefits of this time reduction, in terms of predictable delivery dates and minimal work in progress, are obvious.

But the savings accruing from a 'get it right first time' approach cannot easily be measured in financial terms. The gain in electronics reliability, and general increase in confidence in the quality of the design and manufacture, are powerful factors in gaining the rapid market acceptance that is so important in selling large computer systems in the world market.