"ACCEL"

AUTOMATED CIRCUIT CARD ETCHING LAYOUT

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DISCLAIMER

In the spring of 1964, Sandia Corporation, Albuquerque, New Mexico, found itself requiring certain electronic equipment, primarily printed circuit boards, faster than it could be produced by conventional techniques. To attempt to find a solution, a six-month feasibility study was planned by Dr. George Hansche of the Sandia Field Test organization and contracted to the Thomas Bede Foundation of Los Altos, California. The efforts of the foundation, and particularly of Dr. Iben Browning, its executive director, resulted in some new and novel approaches. The study verified the practicality of putting much of the production of printed circuit boards under the control of a computer. A joint effort was initiated between Sandia, the Thomas Bede Foundation, and a consultant, H. Shutzberger of MAG-NUM Engineering, Inc., Albuquerque, to adopt for use with Sandia computer facilities the approaches indicated by the feasibility study. The authors were located temporarily at the Thomas Bede Foundation during this phase of the project.

The immediate objectives of developing this new computer-controlled production technique were to overcome some of the production problems imposed by the nature of printed circuit boards, and to speed their manufacture. A printed circuit board is an assembly of electronic and electromechanical components mounted on a thin insulating board, and interconnected by isolated conductive paths which are printed or etched onto the board. Each component lead attached to a conductive path, called a node, which serves as an equipotential for the component and all other components connected to the node. The thin insulating board provides isolation between conducting paths as well as support for the entire assembly. At one end of a printed circuit board is either a connector or a set of printed contacts to provide electrical connection with other assemblies. Because the conductive paths are printed on the board's surface, conductors representing different nodes but located on the same side of the board cannot cross. Crossing conductors must be located on opposite sides of the board so they are isolated from one another by the thickness of the board.

The portion of the process of producing a printed circuit board that lends itself to computer operations begins with a design engineer's circuit specification and ends with the physical construction of the circuit board. The process, adapted for computer operation, includes:

1. Conversion of the engineer's design into computer input data.
2. Editing these data for validity.
3. Retention in a computer-accessible library the dimension and performance characteristics of a set of components which have been adopted as standard by the using organization.
4. A method of handling non-standard data to be entered at the time the board is to be constructed.
5. Positioning the components on the board layout.
6. Making the electrical connections by routing paths connecting like electrical nodal points.

The resultant computer outputs are a schematic of the input circuit, a parts ordering list, an assembly drawing, and a mask with which to etch the circuit board. The computer programs for all of the output information are independent subroutines so that various plotters can be used for output. The first set of routines written are for the SC 4020 which is a magnetic tape-to-microfilm converter.

Generalized computer programs are being developed to accommodate design within the following maximum limits:

1. Up to 47 boards per computer run.
2. As many as 36 coordinate points connected by lines or arcs to specify the board perimeter.
3. A standard grid for board construction with square elements 0.025 inch on a side which is the smallest increment of area currently used by Sandia in circuit board fabircation. With this size grid, the maximum size board the system can produce is 144 sq. in. This area can comprise any combination of length and width that remains within the plotter's limitations. Any other size grids can be used but the area would increase or decrease proportionally to the change in grid size.
4. Boards are single layered, but may have conductors on both sides.
5. Up to 1000 components per board.
6. Components may have up to four connections.
7. All programs are coded in Fortran and are to be available as a chain-linked system.
8. Intermediate storage is to be programmed for both magnetic tape and disks.

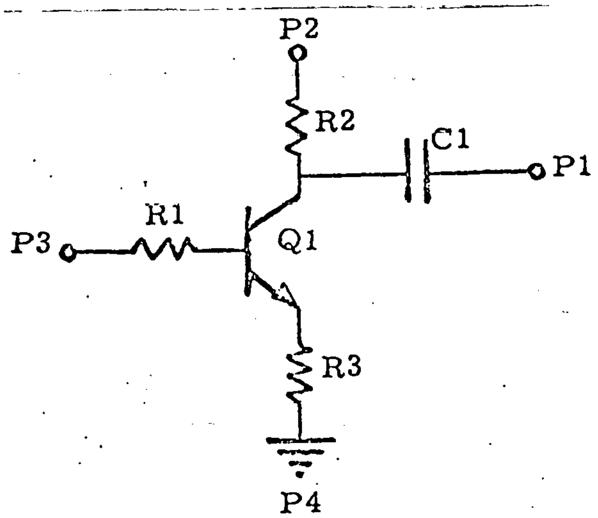
Many variations of the process of entering engineering design data into a computer operation have been attempted in similar projects elsewhere. Highly trained people, quite often the engineer, and expensive machinery, e.g., scanners, digitizers, etc., have been used in these attempts.

The method used in this system, as far as is known is unique. An engineer is familiar with the electrical schematic and uses it as a prime element in the design process. While the schematic represents all the data needed for circuit representation, there is the problem of getting it into a form in which a computer can analyze it. This system uses an intermediate individual of nonprofessional status to make the translation from a circuit schematic to computer code.

The procedure is to arrange the schematic in rows and columns so that every element which is a pre-defined symbol is completely contained within a square. Diagonal lines are undefined symbols. Every crossover, corner or connecting line also appears in a square. When the squares are labeled in rows and columns, x-y coordinates are assigned to each element of the circuit. See Fig. 1 for an example. From reference to a set of standard symbols, the locations and symbols can be diagnosed by the computer to make up a node-parts list. The set of standard symbols can be easily expanded, if necessary, so that an engineer is not unduly restricted in his use of symbols, and so new types of components can be added.

To make a system of this type effective, it is necessary to make component information readily available and easy for the engineer to specify. A library of information on these components which already have been tested for acceptability within Sandia Corporation is to be kept on tape. Hence, an engineer may, for example specify only a resistance value in ohms, and the rest of the parameters for that resistor will be included automatically by the computer. On the other hand, if an engineer wishes to use components that are not in the library, all of the pertinent data must be entered for the computer run and the board will be produced with these components.

Probably the most unusual feature of the system is how the locations of the components on the printed circuit board are determined. The method is called "force placement," because of a close analogy that can be drawn between force and the mechanism which determines the final positions of the components on the board. Force placement is based upon the two main objectives of component placement on printed circuit boards. The first objective is that the components should be placed in positions so that a set of conductors can be routed to connect the circuit properly and cross only on opposite sides of the board. The second is that the set of conductors should be as short as possible. Which objective is more important depends to a large extent on the circuit being packaged. The best introduction for force placement is a simple analogy. Consider the following schematic diagram:



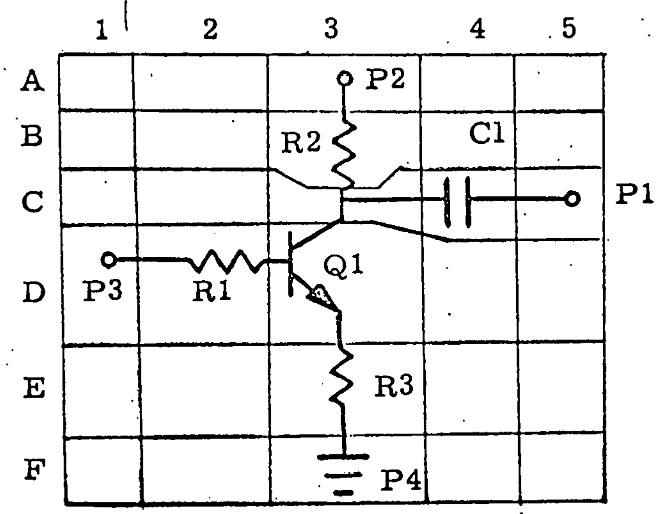


Fig. 1

Imagine that each of the actual components represented has elastic leads which are in a state of tension until they contract to some arbitrarily short length. Further, visualize the components interconnected by their elastic leads as shown on the schematic. The components are placed in an open box whose bottom surface is the size and shape of the printed circuit board surface and whose sides are high enough to prevent the components from spilling over the edge. P1, P2, P3, and P4 are stationary copper contacts which connect to the elastic leads of C1, R2, R1, and R3, respectively. The individual component is constrained by some invisible means to stay in contact with the surface of the bottom of the box. If the components were pinned to the bottom of the box in a random set of positions, some or all of the elastic leads would be stretched and each component would be acted on by a set of forces. If the components suddenly were released from their pinned positions, each would accelerate according to the instantaneous resultant force exerted on it. The components would move into a cluster and stop only after the resultant forces acting on each component provided enough deceleration to stop all movement. At this point, each elastic lead is either relaxed or some other force in the system has prevented it from relaxing, e.g., the repulsive forces between components from physical contact. The motion of each of the bodies after release would depend on the instantaneous force on the body, instantaneous torque, and the first and second integral of linear and angular accelerations with respect to time. Simulation of such a physical system in a computer would be a tremendous problem. Distance relationships would require second integrals of accelerations with respect to time, not to mention the complexity of adding the reaction forces resulting from the components coming in contact with one another.

Fortunately, with the computer we are not limited by physical laws. We are free to define a new universe in which bodies acted on by forces follow laws which we are free to dictate. For example, a component may experience a repulsive force from another component before the two actually make contact. Components even can be allowed to pass through one another if it would be an advantage.

Basically, the universe we define is as follows: The domain of the universe is an area in the x-y plane. It is bounded by a closed curve whose points coincide with the edges of the printed circuit board. The domain contains two-dimensional components which are free to move within it if they are acted on by vector quantities to be called forces. Any component acted on by a force is moved a distance:

(a) whose direction is the direction of the force, and

(b) whose amount is proportional to the magnitude of the force.

A component acted on by a resultant force must move, but a component with a zero resultant force has no means of movement.

Components which are to connect to a common conductive path are acted on by forces which cause them to move toward one another. The further apart these components are, the greater the magnitude of these attractive forces. To prevent the components from moving to positions in which their individual boundaries overlap, a "force of repulsion" has been added. This force of repulsion causes components which are very close to one another to move apart. The magnitude of the repulsive force between two components increases as the distance between the components decreases. To prevent components from being moved out of the domain, a repulsive force from the borders of the domain is defined. Therefore, the three types of forces in this universe are:

(a) forces of attraction between components which connect to common conductive paths,

(b) forces of repulsion between all components, and

(c) forces of repulsion between all components and the edges of the domain.

The force on a particular component is the vector sum of the individual forces contributed by each of the other components and the borders. The force on a component from another component is a function of both components' sizes and the distance between them. The attractive forces and the repulsive forces reflect the shapes of the components.

At the start of the computation, the components are located at random positions on the board. The forces acting on the first component are computed and summed vectorially; the component then is moved in the direction of the force, an amount proportional to it. Next, the computation is performed for the second component, and then the third, and so on until the last component has been moved. This completes one iterative cycle. Several iterative cycles are performed, each successive one based on the new positions resulting from the preceding iterative cycle.

The components move less and less on each successive cycle until a point is reached where the average movement is less than some predefined amount. At this point, an approximate solution has been found to the set of force equations. That is, when the components no longer move in the domain the resultant force on each is zero. There is no overlap of components, because the large repulsive forces prevent it. The components which connect to common conductive paths, however, are physically close together. The final coordinate point associated with each component becomes the component's location on the printed circuit board. Since the lead positions with respect to this point are known, the information needed for the routing program is complete.

An effort was made to improve the routing technique referred to as Lee's Algorithm.[1] A final compromise was accepted which entails essentially attempting to make a connection with an L shaped path and, when this technique fails, resorting to an algorithm slightly modified from Lee's approach. In the sample circuits attempted, it has been possible to connect successfully as many as 70 percent of the connections with L paths only.

When the conducting path is not completed by an L path, the following procedure is followed:

1. A number is assigned to each of the two points to be connected. One point is given the number 1 and the other a large number like 100 or 1000.
2. From the point designated 1, the procedure is to move outward to all adjacent orthogonal matrix elements. After ascertaining that these elements are empty, they are filled with the number 2. From all elements containing a 2, the outward movement continues to adjacent orthogonal elements which, if empty, are filled with the number 3, and so on.
3. The same procedure is followed from the point assigned the number 100, except the succeeding numbers used are 99, 98, etc.
4. By scanning the entire board, element by element, and inserting the 2's and 99's in the first scan, 3 and 98 the second scan, etc., the effect is to "grow" numbers outward in "count-areas."
5. When the two count-areas intersect, a connecting path is made between the two starting points as follows:
   A. Insert pathway-identity symbols in the adjacent-area elements at the point of intersection of the count-areas.
   B. Extend this pathway by a search up the numerical scale toward 100, always extending the pathway in a straight line if possible.
   C. Extend the pathway down the numerical scale from the point of intersection, again extending it straight if possible.

6. After the path is defined, its elements are filled with appropriate node numbers. All of the other count-area elements which were filled in the process are cleared.
7. Proceed to the next set of points to be connected and repeat the procedure.

The routing matrix may contain coded elements which act as isolation elements to conductor paths. This allows for hole drilling areas, component heat sinks, irregular board perimenters, and any other objects that conducting paths must bypass.

After the routing is completed, the information generated is processed with an output plotting program from which the computer generates an assembly drawing and a mask for the board etching. The programs are written to use the aforementioned SC 4020 for these outputs. A Gerber plotter or a Cal Comp plotter also could be used for this output. Sandia is developing a mosiac camera which will effectively increase the output resolution of the SC 4020 by a factor of 10; this increase should provide more than enough accuracy and resolution for this activity.

Some of the future activity planned within the scope of this system includes the generation of modular integrated circuits and expansion of the use of circuit analysis programs. From the latter an engineer could expect to have his circuit analyzed electrically or produced mechanically by the system.

__REFERENCE__
[1]Lee, C. Y., "An Algorithm for Path Connections and Its Applications", Transactions I.R.E., PGEC-10, September 1961, p. 346.