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DIGITIZING PRINTED CIRCUIT LAYOUTS FOR
AUTOMATIC ARTWORK GENERATION

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

by

A. D. Bridegam

OCTOBER 1965

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ABSTRACT

This paper describes the use of a special purpose coordinate digitizer as a programming machine for printed circuit artwork generation. It describes the method of operations, code generation, and benefits of the system.

DIGITIZING PRINTED CIRCUIT LAYOUTS FOR AUTOMATIC ARTWORK GENERATION

This paper reviews preparation of printed circuit artwork by use of a coordinate digitizing system. Before beginning, it would be beneficial to review some of the methods used in the past to prepare printed circuit artwork at Sandia Corporation.

To begin with, almost all circuit artwork evolves from a circuit layout of some kind.

The main point in this paper is to talk about what happens between the circuit layout stage of design and the actual artwork for etching the board itself.

One of the most common methods for artwork preparation in widespread use today is the taping method.

Taping circuit masters is accomplished by placing adhesive strips and spots of foil-coated mylar on a base sheet of mylar. The strips and spots represent conductor paths and lands and are placed on the master by overlaying the base mylar sheet on the circuit layout itself (Figure 1). This manual operation, because of its dependence on the actual layout for direction, is usually done at a scale of 4:1, the scale most normally used for printed circuit layouts. After the entire layout has been taped, the "master" is placed on a vacuum contact printing frame (Figure 2) and reproduced photographically, producing a duplicate master (Figure 3). The duplicate master is then sent to the printed circuit fabrication and etching shop where it is photographically reduced with a reduction camera to the desired 1:1 size. This 1:1 master is used to etch the board. The process, as you can see, is time-consuming, sometimes inaccurate, and costly. In fact, some of the typical component boards at Sandia require 30 to 50 man-hours for the taping process alone.

Another method of artwork preparation is use of a cut-and-strip material on which the desired circuit is cut out, using an Aristo coordinatograph precision table (Figure 4). This method is much the same as the taping method except that the cut areas are peeled away upon completion, leaving clear areas representing conductor paths and lands (Figure

5). The process from this point is exactly the same as the taping method--vacuum frame, duplicate master, photographic reduction, and finally etching.

I think there's no need to point out the man-hour costs and time delay involved in this type of operation. It soon became obvious at Sandia that with the increasing volume of circuit artwork required and the trend towards more compact and tightly toleranced boards, new methods were going to be needed to produce boards. In the fall of 1963 during a study of the problems, several things came to light. One of the most important was that Bell Telephone Laboratories at their Whippany, New Jersey, Laboratory had successfully demonstrated generation of printed circuit artwork using a numerically controlled X-Y plotter and a lighthead device to expose on film a trace of the conductor paths and "photo-expose" the lands by combinations of apertures.

This method produced a high quality circuit master and was extremely rapid when compared to manual methods. At this point, with the feasibility of artwork generation via an X-Y plotter/lighthead combination proven, it seemed the only bottleneck was in obtaining the digital data from the circuit layout and putting the data on punched or magnetic tape to drive the artwork generator. If this could be achieved, a way to eliminate a majority of the manual tasks would be found.

The initial solution to the problem resulted in a specification for a special purpose X-Y recorder or digitizer. By definition, a digitizer is a machine designed specifically to record digital X-Y coordinate data from a graphical record of some sort. In this case the graphical record is a printed circuit layout. I am calling our system a "special-purpose" digitizer because it is just that--a digitizing machine with special features for recording all the data peculiar to circuit layouts in addition to coordinate data plus generating codes for an artwork generating device. The digitizer system is shown in Figure 6.

You will recall that with the other processes for artwork preparation the process involved a series of operations as shown in Figure 7.

However, with the combination of a special-purpose digitizing system and an artwork generator, the process reduced to the series of operations shown in Figure 8.

This combination of a special-purpose digitizing system and an automatic artwork generator provided a Phase I solution at Sandia Corporation for preparation of circuit artwork. This paper concentrates primarily on the input side of the combination, namely, the digitizing system.

The basic digitizing system can be divided into three physically separate but electronically united pieces of equipment.

1. The digitizing table and head (Figure 9)
2. The digitizer control unit (Figure 10)
3. The output devices (Figure 11) (in this case an IBM 870 document writing system).

The reading table is equipped with an X carriage (Figure 12) and a Y carriage (Figure 13). Note that the Y carriage contains a reading head for locating points and a set of readout buttons. Both axes of movement are mechanically connected through a cable/gear drive system underneath the reading table which actuates a set of magnetic encoders (Figure 14), one for each axis, both of which generate 1000 counts per inch of carriage travel. Thus the digital resolution of the system is .001 (one-thousandths) of an inch on either axis.

The digitizer control system, electrically tied to the reading table, looks like this (Figure 15). It is a completely digital system which receives information from the reading table; then, depending on various switch settings, transmits this information to the output devices.

Finally, the entire system is connected to a system of output devices--an IBM 870 document writing system. This system is composed of an 836 card punch/reader and control unit, a 961 8-channel tape punch, and an 865 selectric typewriter unit. This system allows output in the form of punched cards, punched tape, or typewriter verification in any or all combinations.

A functional diagram of the IBM 870 system is shown in Figure 16. The digitizer data enters directly to the IBM 870 system common channel. From this point you can see that the data can be extracted in a variety of ways.

1. Via the 961 tape punch
2. Via the 836 card punch
3. Via the 865 typewriter
4. Via any combination of these three.

With the historical background discussed and the system described, it is now possible to discuss how circuit layouts are programmed into the machine code language of an artwork generator.

As a standard first step, the machine operator places the circuit layout on the reading table and aligns it with the reading head. After fastening the layout to the table, the operator moves the reading head cursor to a desired system origin (Figure 17). At this point he clears the system (Figure 18) and is ready to proceed with the setup. The 870 system is loaded with tape in the tape punch, cards in the card punch, and paper in the typewriter. Switches are normally set to divide the digitized data by 4 if the layout is at a scale of 4:1 (Figure 19). The preparatory function switch is normally set to linear mode (Figure 20). This is done because all motions made by the artwork generator are normally linear motions. The sequence counter is cleared to sequence number one (1) by depressing the clear button (Figure 21). The read-mode switch is normally placed in the absolute mode (Figure 22) which means that all coordinates will be referenced back to the original system origin as set by the operator.

At this point the operator is prepared to digitize the printed circuit layout. An "End-of-Record" code is entered into the tape via the 836 keyboard to provide a "rewind stop" indicating the start of the tape. The operator then enters the code for the first aperture to be used via the operation function thumbwheel switches (Figure 23). Normally, the first aperture selected is a registration mark aperture or "target" as we call it. The proper codes for this function are selected, the toggle switches under the desired codes are turned on and the "operation readout" button is depressed. This action causes the set codes to be typed on the 865 typewriter (Figure 24), punched on a card in the 836 card punch (Figure 25), and entered on the tape in the 961 tape punch (Figure 26). This constitutes one "block" of information. The 870 system is wired such that after each readout an end-of-block code (a channel-8 punch) is generated automatically on the tape. You probably also noted that the sequence number N0001 was placed in front of the desired block of information. These sequence numbers provide operator reference and identify certain portions of the program for later use. The sequence numbers are automatically placed before each block of information and automatically advance between readouts.

Then the operator selects another aperture to be used for back side registration targets (Figure 27). This is followed by "Operation Readout" again, entering the new aperture code on the output devices (Figure 28). Now the operator moves the reading head from the origin to the first registration point to be digitized (Figure 29). The operator then depresses the "main readout" button on the reading head (Figure 30). This records in one block of information the following (Figure 31): the sequence number as

previously discussed; the first machine code (G01) which is an instruction for linear motion. This appears due to setting the "preparatory function" switch to "linear" as described earlier. This is followed by the X and Y coordinate values of the point in question. Note that these coordinates are already scaled down to 1:1 scale by the control unit dividing circuits and that a decimal point is not required. The last code (D02) is an instruction to keep the light off. Thus, this block of information tells the artwork generator to move, linearly, from where it was (0, 0) to the new set of coordinates with the light off. This prevents exposing a line from the origin to the first "target." Now that we are at the point, the only remaining thing to do is to "photo-expose" or "photo-flash" the light such that an image of the registration target appears on the film. This is done by depressing the "photo-expose" button on the reading head (Figure 32). This process continues in the same fashion for the remaining registration points--"main readout" to get there (Figure 33); "photo-expose" readout to expose the "target" (Figure 34).

After the "targets" have been digitized, the most predominant land size on the circuit is selected and entered on the "Operation function" thumbwheels (Figure 35). "Operation readout" follows and the land patterns are ready to be digitized. The procedure, since we are still "photo-exposing", is the same as for the targets--"Main-readout" for linear motion to the point (Figure 36), followed by "photo-expose" readout (Figure 37). For the remainder of the lands, the procedure is repetitious, involving "Main-readout" and "photo-expose" readout at each land position. If there is more than one size of land on the layout, a change of aperture size can be made at any time via the operation function switches and "readout". In a relatively short period of time, this method will record all the necessary data to generate the land pattern of the circuit master. We think of this land information as information common to both sides of a double-sided board since the land pattern is also required on the back side. To facilitate the identification of this information, the last sequence number of the operation is recorded and a "program stop" code is generated by the operator, using the operation function switches and readout as shown in Figure 38.

The next segment of the layout to be digitized is the front side conductor paths. The proper aperture is selected for the first path and digitizing can begin. There is a slight problem in this area due to the current necessity to retain the small "eye" in the center of each land for drilling. Obviously, if the "eye" is to be retained, the conductor path may not emanate or terminate at the center of a land. If it would, the eye would be wiped out or "exposed". Here is a sample sketch of a portion of a layout with the lands and paths represented graphically (Figure 39). It can be seen that the starting and terminating

points for the circuit are offset from the center of the lands by some finite amount which is a function of the land diameter and the path width. To account for this, a cursor was designed for the reading head which could overcome the offset problem (Figure 40). It is composed of a number of concentric circle sets which are numbered and listed in a table of combinations. For each particular land-path combination, there is a corresponding circle to be used in digitizing the path end points. This circle has a finite radius which equals the desired offset for the particular land-path combination. By placing the center of the circle along the path such that the circle passes through the land center like this (Figure 41), the start point can be digitized using the "main readout" button. The path can be made by proceeding to the opposite end in a similar fashion. At the path end point the "main readout" is again actuated but with the light on (Figure 42). This information will bring the artwork generator to the offset start point; then it will cause a path to be exposed to the offset end point.

This process is used to digitize all the conductor paths on both the front and back sides of the layout. Upon completion of all digitizing, the operator selects an "M30" code on the operation function thumbwheel switches (Figure 43). This code is a "tape rewind" code which automatically causes the tape to be rewound to the "rewind stop" or "end-of-record" code at the front end of the tape. After this step, the tape is wound on a standard NAB reel and is ready for use on the artwork generator (Figure 44).

The program, as digitized, can be broken down into three distinct and logical groups. This picture shows the basic structure of the program (Figure 45). The first portion of the tape contains all the information common to both sides of the circuit board. Normally, this is all the land information, registration information, and, if necessary, some path information. The second portion contains information pertaining to the front side of the board only. This is usually path information only. The third portion contains information pertaining to the back side of the board only, which again is usually path information only. The procedure used on the artwork generator is usually as follows:

Generate the common information first.

Generate the front side information next.

Offset the generator head to a new position on the film; apply the X-mirror feature. This produces a mirrored image of incoming data.

Generate the back side information next. Note that this is mirrored.

Rewind tape and regenerate the common information again. Note that this time this information is mirrored.

Using this method, you will note that the same coordinate data used for front side lands and targets is reused for back side lands and targets. This facilitates very precise registration of the circuit layers. You can see that, if desired, this procedure could be used for a multi-layered board with more than two circuit layers producing the same results.

Some samples of circuit masters which were prepared on the artwork generator from digitized programs follow:

1. Figure 46 shows a small master which was digitized in approximately 25 minutes. The average time to prepare a 4:1 master using the tape method is 1 hour. A time reduction to 1/2 exclusive of photo-reduction time.
2. Figure 47 shows a more complex circuit master which was digitized in approximately 5 hours. The average time to prepare a 4:1 master using the tape method is 40 hours. A time reduction to 1/8 exclusive of photo-reduction time.

The data we have gathered so far indicates that the time saved increases drastically with complexity of the circuit layout itself. Another point--if the circuit paths are too complex for digitizing, as in the case of a point defined path or spiral path, then a program can be written by hand and processed via an APT (Automatically Programmed Tools) postprocessor which has been written at Sandia exclusively for circuit work.

Finally, a few additional words about both the digitizer and generator equipment. The digitizer control unit contains a patchboard for changing input/output formats (Figure 48). This allows data extraction for many different applications. Likewise, the 870 document writing system is also fully patchable (Figure 49) for changing output formats and selecting desired output devices. Because of these features we have also been able to use the digitizing system for preparation of engineering analyses programs. These programs are generated using part and assembly drawings and produce such outputs as:

Weights (individual and composite)

Centers of gravity

Volumes

Surface areas

Curve lengths

Moments of inertias

Stress analyses (static and dynamic)

Also, an attempt is being made to program relatively simple 2-axis N/C machine tools using the system.

The generator itself is also being used for other precision work; namely, preparation of optical comparator charts and lofting applications. Some sample comparator charts follow:

1. Figure 50 shows a polar coordinate chart for measuring R-Theta values as an overlay.
2. Figure 51 shows a part profile comparator chart used for direct inspection.

In conclusion, I would like to remind you that this solution is not the end of the line. Indeed, it is only the beginning. Future plans include computer-assisted data generation, which will still include the digitizer as data-gathering device but will reduce the amount of human operator time. A more sophisticated program is slated to follow and will be entirely computer-oriented, working from a rough schematic sketch and eliminating circuit layouts and digitizing processes entirely. This Sandia program, called "ACCEL" for "Automatic Circuit Card Etched Layout", has already been proven as feasible, and several experimental boards have been prepared with the system. It is still, however, several years in the future for practical everyday use. The digitizing process is a reality now and is certainly a practical and desirable method of program preparation.

Figure 1. Layout Being Taped

Figure 2. Vacuum Frame

Figure 3. Duplicate Master

Figure 4. Aristo with Cut-and-Strip Material

Figure 5. Cut Master on Aristo

Figure 6. Digitizer System (Table and Control)

Figure 7. Flow Chart for Old Method

Figure 8. Flow Chart for New Method

Figure 9. Digitizer Table

Figure 10. Digitizer Control

Figure 11. IBM 870 System

Figure 12. X-Carriage

Figure 13. Y-Carriage

Figure 14. Encoders

Figure 15. Control Panel

Figure 16. 870 Functional Diagram

Figure 17. Cursor at 0,0

Figure 18. Clear System Counters

Figure 19. Scale Switches to 4

Figure 20. Preparatory Function to Linear

Figure 21. Sequence Clear

Figure 22. Read Mode to Absolute

Figure 23. Select Registration Aperture

Figure 24. Codes on Typewriter

Figure 25. Codes on Card Punch

Figure 26. Codes on Tape Punch

Figure 27. Select New Registration Aperture

Figure 28. Operation Readout

Figure 29. Cursor at Target No. 1

Figure 30. Main Readout at Target No. 1

Figure 31. One Block of Information

Figure 32. Photo-Expose at Target No. 1

Figure 33. Main Readout at Target No. 2

Figure 34. Photo-Expose at Target No. 2

Figure 35. Select Land Aperture

Figure 36. Main Readout at Land No. 1

Figure 37. Photo-Expose at Land No. 1

Figure 38. Operation Readout (Program Stop)

Figure 39. Sketch of Land-Path Relations

Figure 40. Cursor Closeup

Figure 41. Cursor at Start-Point

Figure 42. Cursor at End-Point with Light On

Figure 43. Operation Readout (Tape Rewind)

Figure 44. Tape Rewinder

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NOOOI
↓
NXXXXX
} COMMON TO BOTH
  SIDES (LANDS)

MOO
NXXXXX + I
↓
NYYYYY
} FRONT
  SIDE ONLY

MOO
NYYYYY + I
↓
NZZZZZ
} BACK
  SIDE ONLY

M30
( REWIND )

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N76175-001
CM1

SIDE ONE

SIDE TWO

CMN76175-001 ISS B

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Figure 47. Complex Master

Figure 48. Gerber Large Area Coordinate Digitizer (GLACD) Patchboard

Figure 49. 870 Patchboard

Figure 50. Polar Coordinate Chart

Figure 51. Comparator Chart