Computer Art: Color-Stereo Displays

Richard I. Land

Leonardo, Volume 2, Number 4, October 1969, pp. 335-344 (Article)

Published by The MIT Press

Leonardo, Vol. 2, pp. 335–344. Pergamon Press 1969. Printed in Great Britain.

COMPUTER ART:
COLOR-STEREO DISPLAYS

Richard I. Land*

Abstract—*The fundamentals of producing graphic designs by a computer are reviewed. Examples of display techniques are discussed, in particular, printers, plotters and display scopes. A novel system of producing color-stereo displays, with which the operator may interact in real time, is considered in detail and examples of the displays are shown. The machine used was the PDP-1 Computer of Harvard University. The basic program for producing the displays was developed by Dan Cohen as part of his graduate research work.*

I. INTRODUCTION

Computers draw, paint, make music, sculpt and do almost anything man can do! Rubbish. Computers do what men tell them to do and nothing more. The instructions may be sophisticated and the results rather distantly related to the initial data but there is nothing inside the 'black-box' of the computer which has taste. That is the prerogative of man. *Computer art* is produced by a sophisticated pantagraph, where the instruction set used is considerably larger than 'magnify by χ' where χ is the value determined by the programer setting the holes on the arms of the drafting machine. If such a machine is carefully operated and the input data is a sketch by Rembrandt, the resulting enlargement may well be deemed art, indeed, computer art of sorts. The fact that we have in this century devised a machine of almost unimaginable complexity and versatility merely taxes man's mentality in finding ways to put it to use and evaluate its results.

The initial intent of many early computers, apart from the abacus and similar mathematical engines, was recreational—to play tic-tac-toe, chess and similar games. It is only recently that the computer has graduated from the accountant's desk-top to the grand-scale instrument capable of advancing whole new industries and making possible man's reach into space. Yet almost every advance of the computer, from Babbage's first conceptions of 1833 to the present, has engaged man's fancy in fiction and games. Today it is usual for the first testing techniques of a new machine to take the form of games or the production of something with creative appeal, such as visual art.

As techniques developed for computer output in visible form, operators seized upon the recreational opportunity thus engendered and began producing images of various forms and qualities. This is another step in the continuum of history, where a new technique readily finds employment in artistic expression. Leonardo da Vinci is justly famed for both his anatomical drawings and detailed observations of fluid phenomena. Both have artistic distinction in addition to their scientific worth.

Since the earliest machines were developed by man, wheels and levers have come to the aid of artists in a variety of designing engines, culminating perhaps in the sophisticated machines used for engraving portions of forgery-proof security documents. The current mixture of chemical and optical techniques being applied defies any simple survey by its diversity. Using popular jargon, one might say that the computer is just another entrant in the media explosion available to the artist. The profusion of work that currently falls under the title *computer art* or *computer graphics* almost precludes any one person surveying the field successfully [1-4]. Any discussion will have to rely on personal experience and limited published material.

Although machine-produced art is in some elements indistinguishable from *computer art*, present-day opinion would likely restrict the term to works produced by the large computers primarily designed for general logical operations and only available in the last 25 years (commercially available in the last 15 years). The trend of modern thought on the subject is inclined also to eliminate from the category of *computer art* those instruments which seem to have artistic expression as their sole purpose, even though the control system used for it is in fact a computer of sophisticated elaboration utilizing combinations of mechanical and electronic elements.

In his *Lumia*, Wilfred used mechanical linkages to program his optical effects, Malina [5] and Schöffer [6] among others, have employed electronic and mechanical control elements in kinetic art, and like so many of the currently popular art objects, my *Chromara* [7] can be driven by a small electronic analogue computer using audio signals as a control input. The designation *computer art* seems destined to remain attached to those art forms produced by a machine originally designed

* Engineer-artist, Division of Engineering and Applied Physics, Engineering Sciences Laboratory, Harvard University, Cambridge, Mass., U.S.A. (Received 14 February 1969.)

for other purposes—the machine becomes an instrument of extra-logical expression only as the result of the operator's intention.

As the computer becomes an obiquitous servant of our culture, at once important to industrial progress and also an indispensible tool of the scientist, many of its features escape the general understanding of the public. Even the largest of today's machines are simple and direct actors of logical commands. Essentially, the process is 'do this', 'do that', where this and that refer to taking data from somewhere, performing elementary operations and putting data somewhere. The operations appear complex by virtue of the conditional logic that may be used and the speed with which long logical sequences may be followed.

One of the drawbacks of the computer revolution is the growth of a new language; this makes many people feel themselves outsiders, intimidated by the new words. It is amazing how fast one assimilates the new terms after working with these machines and then forgets to explain them in ordinary discussion. I will make an effort to introduce special computer language gradually and explain each term clearly. There are numerous projects considering 'artificial intelligence' and whether computers can be considered to 'think' but this falls outside these considerations [8].

II. BASIC PROCESSES

Most people think of computers as adding machines. They are really instruction performing machines where addition is just one of the fundamental techniques for executing an instruction. The operation of detecting a fit or match, for instance, is merely the negative adding of one thing with another and then observing a null result or 'not different'. When we match two lines, we place them together to see if they have the same length. The computer in its own perceptive way takes a description of the lines, their numerical length, and places them together, adding one, subtracting the other and notes the difference. When there is no difference, it declares a match. The modern computer can do this millions of times while man does it once. In this way it was not hard for a computer to scan a print of the Mona Lisa, read the output of a photo-sensitive device and transform these intensity measurements into a printed output using normal alphanumeric characters (letters, numbers and signs of printing) which rendered a remarkable likeness to the original. Artistically, this was primitive but it was an early step in what now seems to be a boundless excursion of computer activity in the arts. In science, the most elaborate use of such scanning techniques has been the enhancement of space probe photographs of the Moon and of Mars.

Perhaps it is easier to explain the artistic use of computers by reversing the usual discussions of computer basics where one first considers the logic used, then the details of *input* information and finally *output* techniques. Once the simple level of operation is clear, elaboration of techniques will be more meaningful.

To start with the third step—the simplest output appears on a plotter. This instrument uses a pen to draw a line on paper and the computer must provide three commands for each point. Horizontal and vertical position relate the pen to some reference point (lower left corner, or center) previously determined and then the command to draw makes a mark on the paper. From this alone it is clear we can draw figures either by points, each with specific coordinates independent of the previous point, or by writing lines where one command to draw is followed by a series of vertical and horizontal instructions, each small enough to provide a smooth contour. Generally, the computer provides discrete incremental instructions which are smoothed out electronically as the pen moves.

To draw a square using the plotter, the only input needed is where to start, say the lower left corner at a certain location in relation to the fixed corner of the plotter page. Then we give instructions for the points one by one along each of the four lines, changing the direction at each of the corners of the square. We might say our picture consisted of a file of locations, the first location being the starting corner, with its associated instruction to draw, and specific points, one after the other, until completion with the final instruction to draw the last point adjacent to the first point. The detail of the drawing will depend on how many points we put in the file, unless the plotter is of a special sort where it makes straight lines and needs only commands for the end points. In this case only the corner points need be specified for a square to be drawn.

With the addition of a computer between the input and output, drawing a square becomes somewhat more complicated but in general much more powerful. First, we must instruct the computer what to read as *input* and what to say as *output*. This matches its internal handling of data with the operator and plotter. Then we must detail the instructions of how to take each input instruction and generate the points which are the only instructions understood by the plotter. Once we have given the computer this *program*, we may, depending on its sophistication, give very simple commands as input and let the computer do all the drudgery of generating the file of points for the drawing. All that is really required for a square is the length of a side, its orientation and the starting point; thus with a computer one can designate a position for the corner, what direction to start drawing in and the size, and let the program do the rest.

For a first composition we might give instructions that ask the computer also to remember the starting position, rotation and size of the design, and systematically change these according to simple rules. Thus we might fill a page with squares which grow and shrink in size, rotate and seem to follow a pattern. We would then have a computer composition of possible artistic merit.

We have essentially two choices at this juncture of programing our computer. As presented, it is clear that the program waits until it has all the information from the input and then it proceeds until it comes to the command which says it has finished. Thus one is required to specify the entire drawing from the onset and merely wait for the completed output, called *batch processing*. The other alternative is to instruct the program to halt from time to time to read a specific input, perhaps a dial set by hand. Using that information in a specified way, the program can proceed with its instructions. Here the operator and computer co-operate in processing the initial input. The progress of drawing the squares is continually controlled by the operator. The only limitation on his freedom of action is imposed by the input *hardware* (knobs, switches, etc.) and the original program given at the start. This direct interaction with an operator is called *real-time computer processing*.

There are many distinctions, advantages and disadvantages with these two major processing concepts but clearly the *batch process* technique requires much careful planning, since no revision is available during the active production. *Real-time production*, on the other hand, usually finds the computer wasting its considerable capacity just waiting for the operator to 'do his thing'.

From a large collection of instruction sets, a machine would be able to produce hundreds of patterns using the square generator as described. We could then throw away those without value and learn from the more successful ones how to make better ones. This might be more fruitful than manipulating the instructions in real-time over-carefully, producing only one or two labored drawings, each very dependent on the momentary whim of the operator. There are many fascinating subtleties in both of these methods and considerable thought should be given to their advantages and faults before becoming too committed to either one or the other. One should also note that there is often an economic question to be considered in making the choice between *real-time* and *batch processing* that complicates the alternatives.

The term *off-line* needs a word of consideration in this respect. Very often a computer does batch processing in its own fast-time and places outputs into storage, for example on to a magnetic tape. Later this tape is used to drive the plotter to produce the drawings. The transfer of the computed output to another station for the hard-copy is termed *off-line*. When the plotter is driven while the processing takes place, it is called on-line, and generally delays the computer operations (costs more money!).

III. COMPUTER FUNCTION

Although the output device must eventually have point by point instructions for any image produced, the computer can deal with an image in a more abstract manner. Certainly any file of points may be logically processed through any conceivable system of instructions but this usually requires excessive machine time and storage, and is cumbersome to control in the program. The first simplification would be to group the points into lines and then specify the file of lines and the operations with the lines. This may be still further simplified by logically describing a family of lines or figures and doing transformations on these compound elements.

As each higher abstraction from the detail of the image is achieved, the program generally becomes more elegant, saving time, storage and labor of the programer. The loss in this progression is intimate control of all details or of some specific detail that may come to appear important after the processing is underway. In every case, one expects to learn from an initial program what modifications must be developed to achieve specific effects in the ultimate result and be ready to change the program accordingly by modifying the initial one or devising an entire new scheme.

The basic instructions of a computer are not relevant here but the notion of *conditional statements* should be clarified. Often the system of instructions will ask for one transformation until some size is reached, then a change to another transformation. Doing one thing and then changing, *if* something happens, is one of the great powers of computers. But it also provides an interesting demand on the initial program, for one must anticipate *all* such conditional alternatives with appropriate instructions.

The major problem in programs is that one gives a system of instructions assuming that the available information coming into processing has a certain form but neglects the special case when the form is different. In such a case the computer may not recognize the input or may try the usual transformation that leads to an unusable result. Having no instruction what to do then, it may halt, or worse, it may blithely continue making something unrecognizable by anyone—'garbage'.

A simple example of this problem is what happens when the plotter of the previous example comes to an edge of the plotting surface. It is useless to have all the points piled up on the edge, so this situation must be tested for in advance and the decision to ignore all points 'off the paper' must be programed. Note that the actual computational transformations generally have to include all these unwritten points, so that later, when the transformations change, these unwritten points will reappear. There are often special built-in program aids that simplify operations of this type which the operator must know.

One of the most challenging problems in computer graphics is the solution of the 'hidden line' problem. This is the case of a figure being represented as eclipsing another and we observe lines apparently disappearing behind an overlying image. The conditional instructions must here seek out the intersections of all lines, test for the line that is supposed to be in the foreground and continue with the transformations, while remembering which lines are to be 'visible' or 'invisible'. Clearly the details and complications that can be encountered here require sophisticated conditional logic.

It would seem relevant to consider how much effort of the artist should go into the program and how much into the input data. The more structure is included in the latter, the simpler the program may be for elaborate results. The opposite seems more satisfactory. The output reflects the ingenuity of the artist when the input specification is minimal and of high generality, and the program incorporates the adaptive instruction sequences.

Up to now the methods for communicating with the computer have not been simplified for the artist and only the mathematician and logician finds simple languages (sets of instructions which may comprise the program) available for most systems. Work is currently in progress on specific drawing languages of sufficient power for general graphic displays. All of this progresses as the hardware for illustrating becomes more satisfactory. The following recent advertisements indicate some of the possibilities:

(a) '*The Adage Graphics Terminal* is a general purpose, user-oriented product line (of input–output equipment) which will meet the needs of a wide variety of disciplines, initially centered in engineering and scientific research but potentially extending to architectural design and business management. These systems are designed to extend man–machine communication techniques by allowing the user to generate, observe and interact with complex images while they are dynamically displayed on a cathode ray tube.'

(b) '*The Sanders Advanced Data Display System 900* features a larger variety of display sizes and speeds than any other comparable system available today. High-speed vector, position and character function generators permit unrivaled density of displayed graphics and alphanumerics. ADDS/900 offers rotation and translation of data, and exclusive graphic overlay on TV or radar video data Data entry devices having a common interface for standard I/O (input–output) data transfer includep hot-pen, trackball, joystick, keyboard, data tablet and cursor control' [9].

IV. INPUTS

Since the high-speed operations of the computer are electrical, the artist has to translate his intentions into the same terms. Electric typewriters are the most common starting point for input, requiring an alphanumeric code for all information being offered. There are several 'drawing' techniques for input called, *Light-pens*, *Rand Tablet* or *Wands*.

Drawing with a light-pen leaves a line on a TV-tube-type face. Input proceeds much like usual drawing but there are many special advantages in the computer-aided drawing, for one may move lines and change the mode of the pen from writing only, to participating in the instruction processing. The *Rand Tablet* is a limited surface (25 cm square) where each point located under the tip of a special pen may be accurately sensed by the computer. On such a surface, any drawing operation may be completely transferred into the computer's electrical terms. *Wands* are now becoming more numerous as devices whose position in space is read into the computer for three dimensional input [10, 11].

Special optical scanning techniques are becoming available and the variety of pictures or images that may be 'understood' by computers is limited only by the expense of the devices. The familiar punched cards and paper tape are merely a translation from the electric keyboard to a more easily stored form of input and generally this storage is further translated to magnetic tape for online processing.

V. OUTPUTS

Computers are designed to produce their results (*outputs*) as fast as possible in an attempt to keep up with the processing speed. Currently this means using some kind of magnetic storage device, such as magnetic tape. Later, what is on the tape may be converted into printed pages, drawings or the control of any imaginable instrument for the production of a result determined by the original program. In the real-time case, speed remains important. The operator must receive the output and comprehend it at a maximum rate for the processing to continue efficiently. This generally means some form of visual output: printed words, pictures or images produced by electrical and optical techniques.

Printers are presently capable of delivering hundreds of lines a minute with hundreds of characters per line. The characters available are generally letters, numbers or symbols used in printing. There is limited flexibility in arranging irregular spacing, overstrikes and the like. The paper must be of a specified quality and size to be handled with such speed. Plotters today are becoming both fast and flexible. In some cases, the pen moves in two directions over a fixed sheet of paper, up to a meter square and of almost any quality, color or surface.

In other cases, the pen moves in one direction only, while the paper moves in the perpendicular direction. In this case, the size of the paper may not be limited in length, only in width, but it must be of a certain kind to fit the moving surface mechanism. Both methods can produce accuracies better than 0·1 mm in locating points and are capable of remarkable renderings. Obviously, the pens may have ink of any color. The major problem is the consumption of time, for the average 20 cm drawing might take several minutes.

The *cathode ray tube* (*CRT*), in which electrons striking the phosphor screen produce a visible trace as in television, is currently being exploited in many ways. The only limit we need consider to writing speed for CRT output is the comprehension of the viewer or the speed of photographic techniques being used. The photographs accompanying this article generally covered about 20 cm square.

The computer could produce the complete color image in less than $\frac{1}{20}$ second but, since the photographs were exposures of 4 to 8 seconds, the computer had to continue repeating the same pattern over and over.

Most of the CRT outputs are single units having active areas about 25 cm square for producing images in black and white. Flicker has been a problem, so generally the phosphor is selected with a long decay time to permit low refreshing rates for the display commands. The image only exists when the electron beam strikes the phosphor, that is, it disappears during the decay time of the phosphor. For the picture to remain visible, the computer must be instructed to repeat regularly the same motions of the electron beam to refresh the image. This differs from television, where the fast changes of images demand fast decay-times in the phosphor and rapid refreshing rates (decay times are generally less than 100 microseconds and the repeat rate of pictures is about 30 times a second).

Color TV tubes are a simple choice for making color computer outputs. These tubes have until very recently all been of the shadow-mask type, where three electron beams are used, each focused on either red, green or blue dots of phosphor comprising the display screen. The information must be properly filtered, so that the three beams at every instant have the correct intensity instruction to produce the required color. Though this is relatively easy in the color TV case, where the information is received in the filtered (colored) state, it is time consuming to make the necessary transformations for generating a full color image from programed computer instructions.

Recently, penetration phosphors for color-display CRTs have been developed that are in layers, so that the energy of a single electron beam determines both the brightness of the color and the hue itself. While requiring the same color-filtering transformations, the operation of a single beam is easier and the detail rendered still has high resolution.

The development of the *storage tube* has helped visual output techniques in the black and white category. Here the CRT screen can be considered to have a memory that may be switched on and off. At the beginning of writing a picture one turns on the memory and writes the picture as fast as one can—it will then persist until the erase instruction is given.

A family of optical techniques are adaptable to computer output. Small-mass mirrors may be moved electromagnetically at high speeds, giving both a displacement or a change of focus. Small changes in pressure, produced in an electrical transducer, may also be used to change the focal length of lenses comprised of liquids within elastic membranes. The fastest technique of all is the control of light sources either directly or by using fast shutters electronically activated. This field of display is limited in development by the specific images produced.

Before leaving output devices I should point out that obviously visual stimuli are not the only ones used for communication with man. Computers can play music directly through Hi-Fi systems and may speak a limited number of words. Fortunately, in my opinion, not very much has been tried in the taste and smell category and when one smells something, it means there is electrical trouble in the machine room! The use of the tactile sense is receiving limited attention at present.

VI. COLOR OUTPUTS

Colored inks for the plotters and printers and the color TV techniques have been mentioned above. These might be considered intrinsic color systems. There are other color techniques not so closely incorporated in systems.

With black and white CRT displays, photographic techniques offer several approaches. Conceptually, the simplest color system is to have the computer produce a red display, photograph it on color film through a red filter, then proceed similarly with green and blue filters making a triple exposure. Processing of the film will then yield the full color photograph. In the same manner, using negative color media, one could separately make the three negatives and combine them in the darkroom, retaining the flexibility of adjusting the color balance at the same time. This process yields the best color reproductions at present.

These techniques require darkroom delay and are, therefore, *off-line* not *real-time* systems. However, it was clear to early TV experimentalists that all one need do is mount the color filters in a wheel and rotate it synchronously with the display. In this way, there are produced superimposed three color images within the eye response time, giving to the eye the appearance of full color. This was the system proposed by the Columbia Broadcasting System (CBS) just after World War II for color television. Note that if the display area is a 25 cm square, one needs a filter wheel nearly a meter in diameter, whirling at about 1000 rev/min.

After trying subjective colors using display techniques, I wanted to avoid the cumbersome large wheel. Ivan Sutherland suggested that the rotating wheel be hand-held close to the eyes like a lorgnette and then several viewers, each with a properly synchronized unit, might see full color. We quickly realized that this permitted stereo separation of the images as well. The necessary device was designed, the computer programs developed and full color, stereo images were easily obtained from any file of display data [12].

Diagrams of chemical molecules, curves of mathematical relationships and vision experiments have been enhanced or made possible by these techniques. Freehand drawings can be made in three dimensions. The draftsman can see the line in space (by stereo illusion) as he is drawing it.

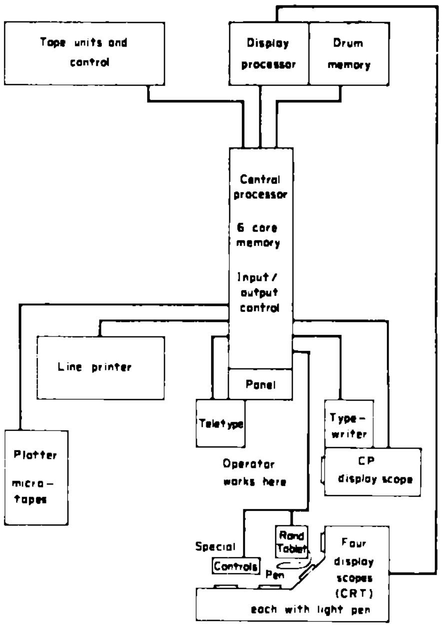

Fig. 1. PDP-1 installation at Harvard's Cruft Laboratory.

The diagram shows the layout of principal units of the computer. All peripherals are connected to the central processor (CP) except the four display scopes that are driven by a separate processor. The scopes receive instructions from the CP and can share the core memory.

VII. EXAMPLES OF COMPUTER ART

1. *The Harvard PDP-1 Installation*

The pictures accompanying this article were produced from displays on the PDP-1 installation at Harvard University. These are a byproduct of research being carried out to enhance man–machine relationships with rapid, unambiguous, high-information content output systems. Since vision appears to be man's widest bandpass sensory channel, the general emphasis is upon display techniques.

The installation shown diagrammatically in Fig. 1 consists of the central processor (CP) unit, its control panel and the peripheral equipment. The input devices include a teletype, paper tape reader, typewriter, Rand Tablet, light pens, switch boxes, rotating knobs and joystick (handle which inputs two directions of motion). In addition, there are magnetic tape units and telephone links capable of very high rates of information transfer.

Information storage can be achieved in several ways, most often in the six cores (arrays of magnetic storage units), or the drum (disks on a common shaft with magnetic surfaces) or the magnetic tapes. The output devices include a high-speed line printer, a plotter, four cathode ray tube (CRT) display consoles (the fifth is generally used only for editing programs), a Hi-Fi amplifier and speaker, and a number of other special devices.

For the uninitated, I will attempt to explain the purpose of the above items. The central processor (CP) is the 'brain' of a computer where the basic instructions are executed, from which all the rest of the equipment gets its instructions or to which the equipment gives information. The CP works directly from the core memory, various special input channels and with several instruction performing registers, called the *arithmetic unit.*

While remote units may continue without specific instructions from the CP, they only start on command and usually tell the CP when they have completed a job and are ready for another one. The instructions to the CP are executed in serial order, with the possibility of skips and jumps called for by the program. The CP is like a master chef who sees to it that all the other kitchen helpers do their job, while he supervises the procurement of food, makes all the important decisions and keeps the whole operation on schedule.

Often a special typewriter or a data-logging device prepares a punched paper tape for use during run time. This off-line prepared input information, including instructions and data may then be run through the paper-tape reader or easily stored for future use. A teletype and typewriter are alternative devices for putting instructions and alphanumeric data directly into the program under way or for manipulating the major processing operation of the entire system.

A Rand Tablet is a handy surface; its million points may be read as a pair of co-ordinates (x, y) by the computer, upon which one may by hand draw or trace a drawing for the computer to 'read'. Depending on the program that one devises to be 'read' from the tablet, the computer can acquire symbols, data or solely graphic elements. The tablet can, in addition, act as an instruction input device.

Light pens give similar results when used in conjunction with the CRTs and a proper pen 'reading' program. They offer the operator the chance of interacting directly with a drawing that the computer is in the process of displaying or to change, elaborate or give additional information. The switches, knobs and joystick may be used to provide continuous control of variables in the program while processing continues.

The magnetic tapes permit a large amount of data to be transferred and very great storage areas to be used. Generally, drum storage area is used as a back up for core storage. Though it is of large capacity it acts as an intermediate storage with slower retrieval speeds than the cores but faster than other larger storage devices.

Although I have already mentioned the plotters and printers, the CRT consoles demand further explanation. The main computer would be greatly delayed in its operations if all it could do was give point by point instructions to the CRTs themselves. In the PDP-1 system being described, the displays are actually controlled by a second or auxiliary computer driven by *Central Processor* (CP). This auxiliary computer receives special instructions and then proceeds to do the rest of the drawing without consuming valuable CP time. Thus, one may

Fig. 2 Color-stereo display in use.

The operator looks through a hand-held rotating filter wheel held close to the eyes. Switches automatically change the colours of the display. The knobs on the left control the stereo depth illusion. Note the stereo filter wheel (uncolored) resting on a piece of paper.

designate a starting place in the memory at which the display is to begin and it will find the place and thereafter follow previously deposited instructions. There are many special instructions that permit communication between the two computers. For example, the light pens may interact with an image so that the program may be changed by virtue of what it has just accomplished (the point 'seen' by the pen). The advantage of having the auxiliary computer figure out character symbols, lines of a previously described nature etc. is that the operating program in the CP is greatly simplified and speeded up.

The hand-held, rotating filter device incorporates a small motor that is synchronized with the computer in such a way that the orientation of the disk mounted on the motor is known at all times. Thus, if the disk is half opaque, the computer knows when the left eye can see and only displays the view for the left eye. When the disk exposes the right eye, the display changes to right eye information and thus provides almost simultaneous stereo views giving the illusion of depth.

By writing on the Rand Tablet and moving the joystick back and forth for the third dimension, the unique experience has been developed where one may draw in space and see the result 'spacially' at the very time it is drawn. One needs considerable time to get used to the experience and, as we do not seem to be naturally adapted to space sketching, one particularly needs practice with the technique in which the pen and the sketch are in different spaces.

Color is easily added to the display by using color filters on the rotating disk. When the eye is looking through the red filter, the computer draws in white what is seen as red and, similarly, for blue and green. The colors may then be additively mixed so that a line drawn in both green and red will appear yellow, a line drawn twice in red and one in green will appeared orange, etc. Indeed, the sequence used for stereo color views is to have a six sectored filter disk with red, green and blue filters interposed by opaque sectors. Thus, when the right eye is eclipsed, the left looks through a filter, etc. The computer essentially displays six renderings in continuous sequence (red-right, blue-left, green-right, red-left, blue-right, green-left), synchronously as the color filters change so fast the eyes only see the sum of all the displays. Typically, one complete cycle of the six sectors takes 50 milliseconds, that is it repeats twenty times a second.

The photograph in Fig. 2 shows a demonstration of a hexagon (each of whose sides is a different color) with two rhomboids and a rectangle inside. The switches permit selection of the color of the central objects. The knobs at the left adjust the depth desired (hence the stereo separation which is calculated by the CP). Important to this system is the type of display screen chosen for the CRT. It must both provide enough intensity for each color filter in the system and be fast in the time it takes to darken after stoppage of excitation by the electron beam which writes the display. The P-4 phosphor surface used in the display screen is not an ideal white but has a large fast blue response and a slower and weaker yellow-green response, all rated at less than 100 microseconds decay time. (The decay is exponential, yet one may *still see the*

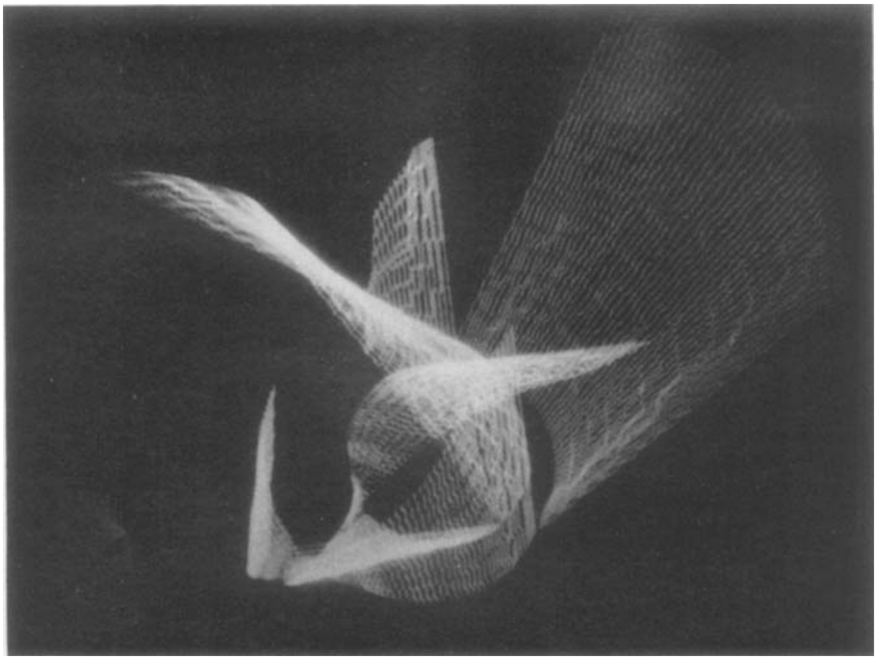

Fig. 4.

red component of this phosphor persisting at an observable level for what must be more than 20 milliseconds, 200 times the rated decay time.)

One should be aware that the spectral character (detail of color absorption) of the filters, photographic materials and printing techniques all served to degrade the color effect seen in Fig. 3. To the observer watching the computer display the colors are highly saturated and cover a wide range of hues. With little effort, more than 30 colors in a single image may clearly be distinguished.

2. *Color 'flowers' and 'birds'*

As part of his graduate research program, while working on a variety of display interactive programs, where the operator consciously interacts with the display, Dan Cohen developed the basic program for the computer art shown here. I merely adapted the program to the color system, adjusted the constants to suit my taste and made the photographs. (Kodak Ektachrome, EHB-135 film, about 4 sec exposure at f/2·8 through one eye hole of the filter wheel.)

The 'Flowers' and 'Birds', as I call the images produced on the display, are sensitive to initial values set for the program, as well as to the many controls operated while the program is in progress (cf. Figs. 3 to 6). Essentially, the program generates a line. This line or vector has two controls which move the starting point (one end of the line) in two circles of different diameter and a third control which rotates the line itself in a circle. The number of lines in any given display may be selected up to some fixed maximum (in most of the illustrations about 500). Switches permit adjustment of the color synchronism, the stacking of displays one over the other, erasure of the image for a new start and the freezing of a pattern so it will stop evolving while a photograph is being taken.

The observer views the 'Flowers' and 'Birds' through the hand-held rotating filter wheel synchronized with the display on the CRT. The pattern normally is changing continuously, evolving into successive patterns under the operator's control. The computer also continuously generates new instructions for the positioning of the line and stacks these one after the other in a memory file accessible to the display processor.

Perhaps the most fascinating aspect of the 'Flowers' and 'Birds' is the simple circle generating sub-routine (a small program used repeatedly by the main program) which positions and rotates a line. The discontinuities present in the circles are the result of not keeping the circle generation continuous but allowing a mathematical error to go uncorrected. Also there is a routine in the program which carefully prevents the lines from intersecting the margins of the display area (about 25 cm square).

3. *Other examples of computer art*

Life Magazine [13] recently featured several pictures of computer art. One picture demonstrated the use of the alphanumeric high-speed printer to produce what looks from a distance like a half-tone print of birds against a cloudy sky. There were also examples of off-line color techniques.

In the course of study of image processing and pattern recognition, John Mott-Smith [14] has developed several techniques of computer art. Currently his work is being exhibited internationally and he has been commissioned to prepare material for *Life Magazine*. He has developed displays both

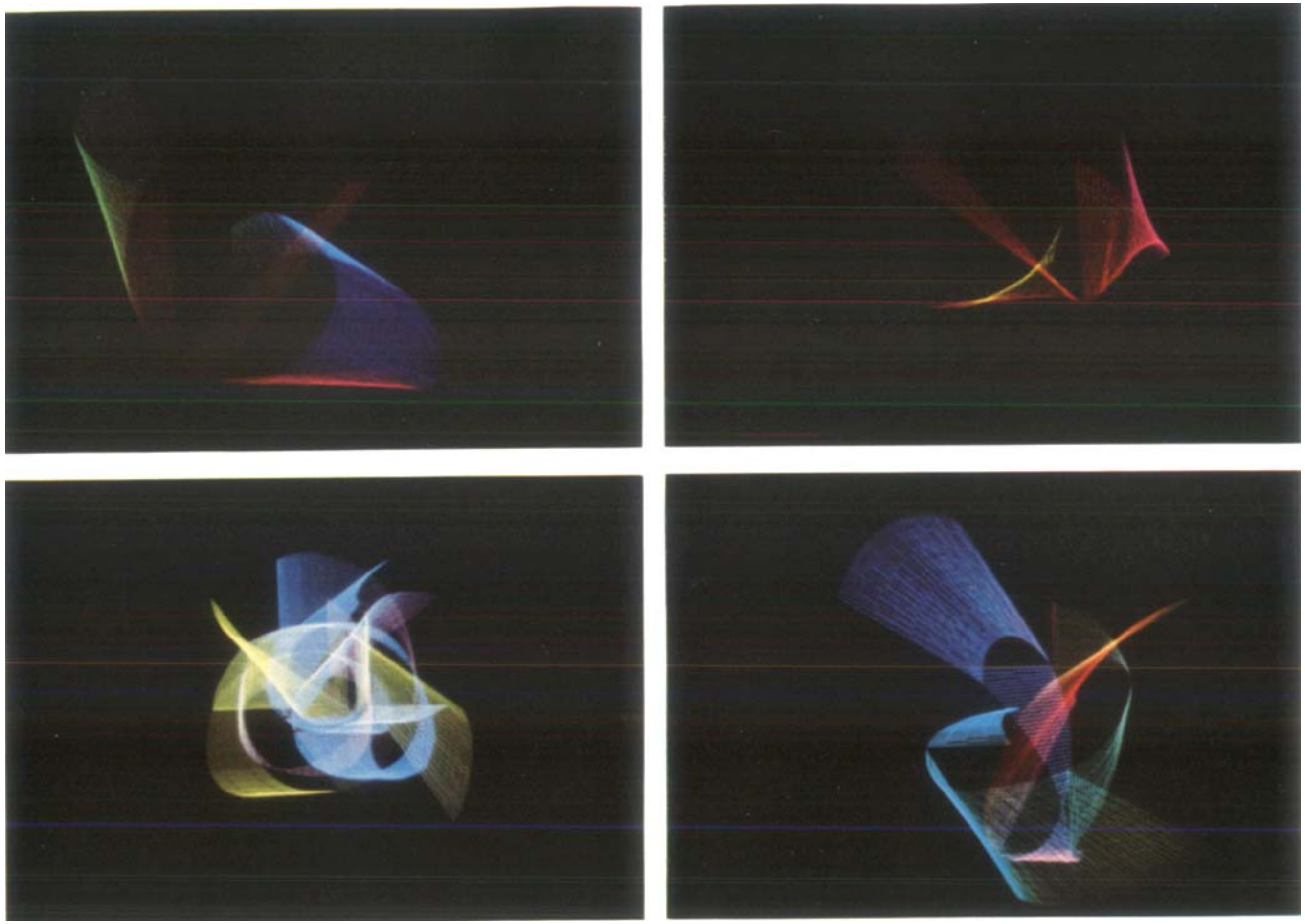

Fig. 3. Color images produced by the Harvard PDP-1 computer under control of the author.

[facing p. 342]

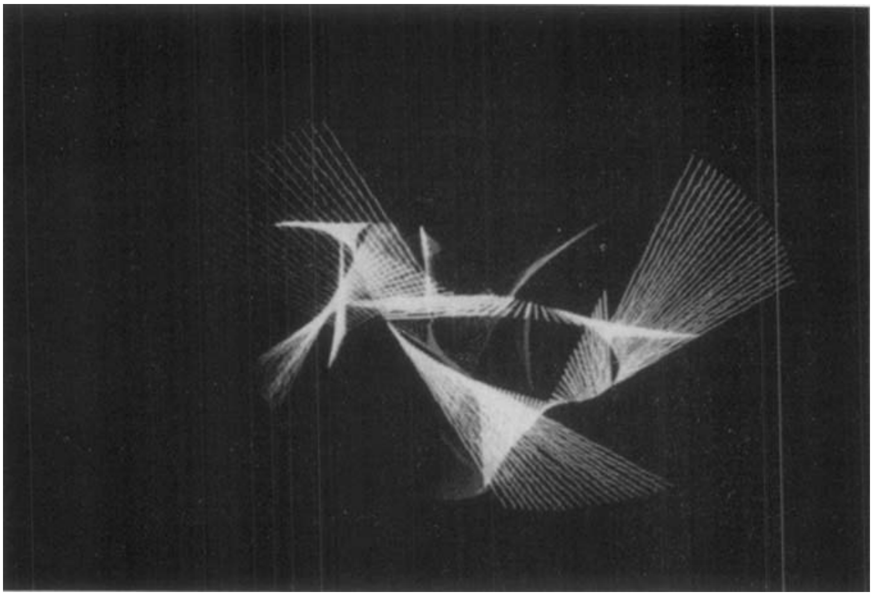

Fig. 5.

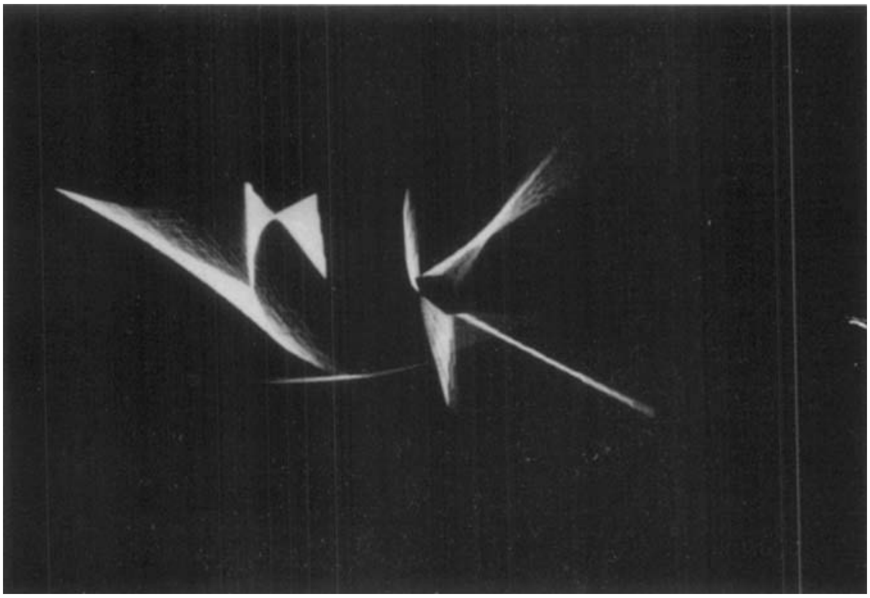

Fig. 6.

Figs. 4 *to* 6. *Image produced by the Harvard PDP*-1 *computer from a program by Dan Cohen and the author.*

in real-time and delayed-time for still and moving photographic techniques. He has apparently developed considerable flexibility in the handling of color, including the use of shadow-mask display tubes, synchronous filter techniques and individual preparation of color-separated negatives.

Working with the Cognitive Information Processing Group at the Massachusetts Institute of Technology (MIT), Charles Seitz has produced a fascinating series of dynamic programs which include sound. One may observe dancing circles and delicate 'splashes' with trills of notes that actually sound as though they belong to the pictures. Seitz's visual programs are run on a PDP-9 computer and the sound comes from a loudspeaker driven by an amplifier using the x-deflection signal for the display as an audio signal.

Bell Telephone Laboratories have been involved in numerous display developments. Perhaps most attractive to artists are the programs that provide animation routines. Used in technology, they may design electrical circuits by gathering the electronic symbols into appropriate connected arrangements and then allow the computer also to display the characteristics of the electrical behaviour of the circuit so designed. Much of this type of animated display interaction stems from Ivan Sutherland's *sketchpad* innovations [15].

Other large industries have developed special graphic systems. In reference 16 it is stated that: 'The Electronics Laboratory of the General Electric Co., Syracuse, N.Y., has developed a computer generated simulation technique that involves: (1) storing the data describing the environment in computer memory; and (2) solving in real time the perspective equations that define the environment image on the display or image plane. All hardware for modelling and photographing in connection with the simulated display is eliminated and replaced by a computer with numerical data stored in its memory. A color TV monitor or set of monitors shows the actual display using a purely mathematical-scanning and perspective-image-computation process.'

General Motors Research Laboratories had the IBM Corporation design special computers for them. One of these, the DAC-1, permits the usual interactive drawing and data handling, and can also produce large photographic prints from precision negatives and use data from scanned drawings as computer input. Another computer can form a full-scale model of an automobile in clay from numerical specifications, taking about thirty minutes for the job.

VIII. CONCLUSION

Perhaps the computer is more than a new medium. It is a challenge to artists in all media to learn the characteristics of this powerful tool and the ways in which it may give wider scope to their talent. Talent, taste and intuition must be brought to the computer by man, it has technique to spare. There is one major problem at present—computer time is very, very expensive.

A Computer Arts Society has been organized in London and interested persons may obtain information on it from Alan Sutcliffe, ICL, Brandon House, Bracknell, Berks., England [17].

ACKNOWLEDGEMENTS

My work with computers and related studies could not have been accomplished without the encouragement of I. E. Sutherland and the help of Dan Cohen among others, at the Harvard Computation Laboratory and, of course, without the basic support of departments at Harvard and of Grant No. F 19628-68-C-0379 from the Advanced Research Projects Agency of the U.S. Government.

REFERENCES

1. Cybernetic Serendipity, Ed.: Jasia Reichardt, *Studio International*, Special issue (1968).
2. L. D. Harmon and K. C. Knowlton, Picture Processing by Computer, *Science* **164**, 19 (1969).
3. 6th Annual Computer Art Contest, *Computers and Automation* **17,** 8 (Aug. 1968).
4. 7th Annual Computer Art Contest, *Computers and Automation* **18,** 8 (Aug. 1969).
5. R. Gadney, Aspects of Kinetic Art and Motion, *Four Essays on Kinetic Art* (London: Motion Books, 1966) p. 26.
7. *Nicholas Schoffer* (Neuchatel: Editions du Griffon, 1963) p. 50.
6. R. I. Land, Non-verbal 'Discussion' using Music and Kinetic Painting, *Leonardo* **1**, 121 (1968).
8. Information and Computers, entire issue of *Scientific American* (Sept. 1966).
9. Advertisement of the Sanders Advanced Data Display System /900. *Scientific American* (Feb. 1969).
10. L. G. Roberts, The Lincoln Wand, *FJCC Proceedings* 29 (1966).
11. A. E. Brenner, Sonic Pen Discussion and Private Demonstration of Unit at Dunbar Laboratory, Harvard (1969).
12. R. I. Land and I. E. Sutherland, Real Time, Color, Stereo, Computer Displays, *Appl. Optics* **8,** 721 (March 1969).
13. Luminous Art of the Computer, *Life Magazine* (Nov. 9 1968).
14. J. Mott-Smith, Private Discussion and Demonstration, Air Force Cambridge Research Laboratories, Bedford, Mass.
15. I. E. Sutherland, Sketchpad: A Man–Machine Graphical Communications System, *M.I.T. Lincoln Lab., Tech. Rep. No.* 296 (Jan. 30 1963).
16. Visual information displays systems, *NASA*, *SP*-5049, U.S. Govt. Printing Off., Washington, D.C., U.S.A., 1968.
17. Notes, Communications, *ACM* (Jan. 1969).

Art automatique et programmé (par ordinateur): images colorées stéréoscopique

Résumé—Les principes fondamentaux de la production de dessins graphiques par un ordinateur sont étudiés dans cet article. L'auteur décrit en particulier des exemples de techniques de représentation d'images au moyen de machines imprimantes, de machines traceuses et d'écrans équipés de tubes à rayon cathodique. Des détails sont donnés sur un nouveau procédé de production de couleur au moyen d'images stéréoscopiques. Un opérateur peut intervenir en temps réel dans ce procédé. Un certain nombre d'exemples d'images obtenues suivant ce procédé est étudié. La machine utilisée pour cela est l'Ordinateur PDP-1 de l'Université de Harvard. Le programme de base utilisé pour produire les images a été élaboré par Dan Cohen au cours de ses travaux de recherche comme Maître Assistant.