MECHANICAL CHARACTERISTICS OF BINARY PLOTTING DEVICES AND THE TRANSFER FUNCTIONS OF RELEVANT CONTROL SYSTEMS

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ABSTRACT

Important parameters which determine the effectiveness of plotting systems are visual acuity, accuracy of plotting mechanisms and the transfer functions embedded in their control systems. To relate the limits of visual acuity to the concept of aesthetically pleasing graphics invokes the notion of 'visual noise' in drawings. While the 'step size' is of overall importance, a high degree of 'squareness' is unnecessary to many application areas. Special hardware should be provided for drawing circles, sloping lines and alphanumerics. The realization of such hardware introduces new and exciting processing applications. Plotting systems might become dynamic input generators for synthesizing processes.

ABRÉGÉ

Les paramètres importants qui déterminent l'efficacité des systèmes de traçage sont l'acuité visuelle, la précision des mécanismes traceurs, et les fonctions de transfert incorporés dans les systèmes de contrôle. Il faut invoquer l'idée du 'bruit visuel' pour établir une relation entre les limites de l'acuité visuelle et le concept de la graphique esthétique. La grandeur du pas a une importance générale mais pour beaucoup d'applications, il n'est pas necessaire d'avoir une forme bien 'carrée'. On devrait fournir un équipement spécial pour tracer des circles, des lignes inclinées et des caractères alphanumériques. L'introduction de cette sorte d'équipement permet les applications nouvelles dans la domaine des processus. Il semble possible que les systèmes de traçage deviennent des générateurs dynamiques d'entrée pour les processus de synthèse.

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A binary plotter is a device designed to convert digital input information (called instructions) into large scale precision computer graphics. This graphic results from a relative movement between the plotter's 'line media' and its 'recording surface'. All such relative movements are generated through only two types of instructions:- 1. create a fixed 'increment movement', parallel to either of the co-ordinate axis. 2. raise or lower the line media.

There is normally a separate instruction and a dedicated control line for each of the six co-ordinate directions (+X,-X,+Y,-Y,+Z,-Z).

The Line Media is the part of the plotter instrumentation which can leave a trace on the recording surface. It can be a pen, pencil, electric beam or scribing tool.

The Recording Surface is the surface the line media leaves its trace upon. It can be paper, film or metal.

An Increment is a unit of measurement set by manufacturer specifications. It is often called the 'step size', and is normally in the range of 0.001 to 0.005". This is the basic unit all graphics are composed from. The instructions for such compositions are provided by the plotter's control system.

An Instruction is an electric signal constituted by an appropriate change in voltage level, for a specific period of time called the pulse width, on any of the six control lines.

Three aspects of plotters and their control systems are significant to the user.

1. The mechanical requirements of digital plotting devices.
2. Control mechanisms: Alphanumerics, straight lines between any two points and circles, are graphics the plotting system performs repeatedly. It accomplishes this through software programs or dedicated hardware. Such hardware organization is called a 'plotter controller'.
3. The plotting system has historically been used exclusively as an output device. However, its use as a dynamic data generating device for the design synthesis process is emerging through the expanding facilities of its control mechanism.

Mechanical Requirements

There are only 3 basic technical properties to consider when assessing the suitability of a plotter:- a. step size. b. accuracy. c. operating speed.

You see references in the literature to 'resolution', 'repeatability' and 'line quality'. These are merely functions of the step size and the accuracy, and will be discussed in their correct relevancy.

When we talk about accuracy, we refer to the machine's ability to provide an accurate step size consistently. The step size is important because it determines the visual appearance of the line. To understand its visual parameters we must look into certain characteristics of our eye:-

The human eye has a resolution of about one minute of arc. Finer features than that can normally not be recorded by it. See Fig: #1. The formal unit of measurement for the eye's resolution is called 'visual acuity'. It is the inverse of the angle A on Fig: #1. Visual acuity varies with the contrast, e.g., black line against white paper, and the illumination. A drawing where two lines overlap and the skew exceed one minute of arc, is esthetically unpleasing because the skew is recorded by the eye as a buldge on the line. See Fig: #2. In drawings viewed at a distance of 14", the skew would have to be less than .004" ($2*\sin(\frac{1}{2})*14"$). Since digital plotters are only accurate within one increment, the step size should not exceed .004" in order to be acceptable from an aesthetic point of view. However, under certain conditions a sharp eye can decern features with a view angle as small as .4 minutes of arc. If the skew of two lines is a sharp offset as in Fig: #3, the eye can record a 'view angle' as small as an alarming 4 seconds of arc. The ability to record such acute shifts in direction is called 'vernier acuity'. Yet we know that in drawings, the eye cannot decern vernier acuity with such accuracy. This is probably because all other lines on the drawing reduce such offsets to 'visual noise' which is passed over by the eye. A line is resolved clearly by the eye if its width is at least one minute of arc. The eye resolves it even if it is less than that, but it is then probably picked up only as a visual noise.

Proper data on noise in drawing does not exist and should be researched.

However, in lieu of such data, it is felt that a plotter, because it draws lines which involve vernier acuities, should feature a maximum step size of .001".

<u>The Accuracy</u> refers to the accuracy by which the plotter draws the increment to the specific length given in the manufacturer's specification. The nominal increment size is the parameter used by the plotter's control system to determine how many increments a line is to be made up of. Thus the 'accuracy' determines the accuracy of the length of any line the plotter draws.

There are three main causes for possible deviations in 'accuracy'. All relate to the mechanism which translates the increment-movement from the increment generator to the line media:-

a. the mechanism delivers an increment with a standard deviation.
b. the mechanism delivers an increment with a deviation which is a function of the line media's co-ordinate position.
c. the mechanism delivers an increment with a random deviation.

In the case of constant deviation, drawings may be free of blemishes and be aesthetically pleasing, but would not be completely accurate. Still the drawing may be repeated any number of times with no apparent distortion. In a case where the deviation varies with the pen's co-ordinate position, there will exist distortions between the two outputs of the same data drawn on different parts of the recording surface. This problem can be substantially alleviated on flat bed plotters because drawings can be mounted in the exact previous location by reference points on the surface table. In the case of random deviation, its accumulated effect anywhere within the draughting surface (for flat beds) should not exceed the relative limits of acuity of .001". The acceptable degree of accuracy depends on the specific application. Fine deviations are, for instance, of no importance in architectural drawings, while they might not be acceptable in drawings used as production masks for integrated semi-conductor circuits.

<u>The Repeatability</u> is a resultant of 'accuracy'. It refers to the deviation found between two points X1, Y1 and X2, Y2, which are referenced at different times in the draughting routine, and where X1=X2 and Y1=Y2 (e.g., the same point). The 'repeatability' is not a constant variable but is a function of the number of increments occurring in the interval between the line media leaving a given point and its subsequent return to it. The visual effect of poor repeatability is such that if a line in a drawing is repeated after a set of intermediate operations, the user may notice a broadening of the line, equivalent to the amount the offset of the centre line exceeds one minute of arc. This will be especially noticeable if the line is repeated for only part of its length. An even more noticeable effect could appear when the pen approaches a point from the opposite direction of its previous move to that point. In that case, the poor repeatability due to random deviations, might cause a given point to appear as two entirely separate points. In effect, the repeatability sets the limit of accuracy and in turn, the step size.

The Resolution is the process by which the eye can differentiate a line into its component increments. This, of course, is another term for visual acuity. Thus it is silly to talk about the resolution along the length of a straight line consisting of a continuous set of only X or Y co-ordinate increments. However, resolution is very meaningful if you want to determine when a string of dots will be seen as a continuous line. The effect of resolution is the main proponent of line quality. Another proponent of line quality is the hardness of the recording surface. Due to vernier acuity, line quality is basically difficult to obtain in lines which have a slope different from 0, 45 or 90 degrees. In these cases, the line quality is a function of both the incremental step and the resolution of points along the line provided by the plotter controller. All sloping lines are produced by moving the line media along the X and Y axis congruant to the co-ordinate slope of the line. Due to the problem of vernier acuity, it is important that the pen can move in both the X and Y direction simultaneously. So any two sequential increment movements along a sloping line will either be in the same direction, or at a 45 degree angle to each other. If the basic plotter step is greater than .001", the line will appear as a saw-tooth regardless of other qualities in the plotter. As the basic step of the plotter decreases, irregularities in line composition become less noticeable until they can no longer be resolved by the eye.

The Operating Speed is determined by two mechanical factors:-

1. the time it takes the line media to move one increment. (a fast plotter draws typically 10" of line per second. With an increment of .001" it must draw 10,000 increments per second.)
2. the time it takes the line media to lift clear, or set down on the recording surface. (this takes typically, a few milliseconds).

The electronic processing speed of the plotter controller can be ignored in computing plotting speeds because it is so much smaller than the time delay, caused by mechanical factors. Thus the plotting speed is made up of a composite of time delays resulting from horizontal and vertical movements of the line media.

Other Mechanical Aspects. High quality plotters are very expensive. This is due in part, to their sturdy construction. (Prior to building plotters, some manufacturers used to make guns or heavy precision equipment). One argument for sturdy construction is the scientific degree of squareness in plotters. The squareness is the deviation from 90 degrees of angle between the X and Y co-ordinate axes. On some plotters this is less than 8 seconds of arc. Such accuracy might be valuable in some scientific applications, but not in most design areas due to the element of visual noise. To produce adequate, but much less expensive plotters, would probably call for greatly simplified construction. For instance, some manufacturers go to great expense to provide a steel plotting surface, milled to within a few thousands of an inch. Paradoxically, hard surfaces are bad for line quality when the line media is pen or pencil. Notice draughting boards in architectural offices: they have soft wooden surfaces, carefully covered with thick soft paper or linoleum to assure nice line quality. Plotters should be built the same way. Both the light table construction and soft, recoverable surface should be maintained. Plotters should just be draughting machines under mechanical rather than hand control. The method employed to produce the relative movements is a sales feature to many manufacturers. However, whether the drive mechanism is a magnetic field, stepping motor with a sturdy gantry or a heat print process, has no importance - only the cost and performance really matter.

2. Control Mechanisms

Every increment the plotter draws, and each change in the vertical position of its line media requires a separate instruction pulse. Thus anything it is to carry out, whether to draw a circle or line, must be responses to a long string of instructions. To get a feeling for the number of instructions often required, note that an architectural drawing which has approximately 1000" of line, requires more than one million increment instructions. Quite evidently such masses of instruction could become excessive for both storage as well as for computer-plotter interface. A fast plotter takes 100 microseconds to execute an 'increment' instruction and much longer to execute an instruction to change the pen's vertical position. The computer processor requires only a very few microseconds to transverse a transfer function required by the plotter operation. Thus, if the main-frame processor was 'on line' with the plotter it would have to be idle about 99% of its potential processing time while it waits for the plotter to be ready to receive the next instruction. Conversely, it takes the computer about 10 nano-seconds to forward an instruction to the plotter via its 'bus' system. If the main frame processor is to produce the instruction string, there are two ways in which it can reasonably do so:-

1. store the plot instructions, as they are produced, on an auxilary storage device for subsequent transfer to the plotter.
2. switch processing tasks between each data transfer.

The first alternative will cause a very substantial increase in the computer's processing time due to the data transfer. The second alternative will require about one million switching cycles during the drawing of a typical architectural drawing. Most of the required instructions could be generated 'on line' with the plotter by some facility which is part of the plotting system. The generation of these 'on line' instructions, can be provided through a set of transfer functions which will produce them from much simpler data structures. Such basic transfer functions could reside in a separate 'controller' which will generate data by hardware functions. A controller is a 'stand alone', special purpose processor whose sole task is to perform a set of required operations under certain conditions. The application of a plotter controller will, in effect, allow for parallel processing between the host computer and the plotting system. We must ask what transfer functions we wish the processor to be capable of performing. We saw in the beginning of this paper, that the plotter could execute two different types of instruction. The first was to draw a line increment, the second to raise or lower the line media. In the logic design for a plotter controller, there are two distinct classes of transfer functions we must accommodate. They map right onto the two types of instructions.

1. those which generate the path the line media must follow.
2. those which determine the type of trace we want the line media to leave on its path along the recording surface.

There are several levels of transfer functions of each type. Each of these levels is the antecedent of the next level. The function of the next level is accomplished through a special application of its antecedents. We have three levels of the first type:-
a) sloping line. b) circle. c) alphanumerics and circle mutations.
We have two levels of the second class:- a) trace types. b) hatching patterns. Each transfer function generates a special set of plotter instruction in response to a given minimal set of input data. We can make the general data assumption that the starting point on any path for the line media is the current position of the line media.

Type 1:
Level a-sloping line - this transfer function generates the instruction set required to draw a straight line from the current line media location to a point X2, Y2. The only data provided is the values for X2 and Y2. This is accomplished by gating the X2, Y2 values through inverter gates (SN7404), then using those outputs and the values of X1, Y2 as input to adder gates (SN7483). The resultant sums are then passed as rate input to rate multipliers (SN7497). The output from those constitute the X and Y increment instructions.

Level b-circle - this transfer function generates the instruction set required to draw a directed circle, or a given arc thereof. The only data required is the radius, direction, starting point on the circle and arc size. For architectural purposes, the circle may be drawn as 24 or 48 cords. See Fig: #4. Thus the circle is accomplished by generating a set of cords, each of which is a sloping line of level a. The rate input for the line is provided by a hardwired sine / cosine generator.

Level c-circle mutation - this transfer function generates the instruction set required to draw a circle as a rectangle, or as a straight line. (See Fig: #5, a,b,c,d). The square in Fig: #5b, is generated by a regular circle instruction. However, the X and Y output increment pulses cannot occur in the same quadrant, they are alternately inhibited by a flip-flop which is pulsed whenever X or Y becomes 0. The rectangle in Fig: #5c, is generated by way of the above squaring method. However, in addition to this, the shift register storing the radius value is pulsed for a shift towards the most significant bit when Y becomes R, and toward the least significant bit when X becomes R. A straight line is produced by locking the X or the Y outputs at zero during the drawing of the circle. If the shifting of the radius had been applied without the squaring method, the circle would have become an elipse. That feature is very important when it comes to changing the relative proportions of alphanumerics.

Level d-alphanumerics. The circle generator will draw any number of cords requested in a single instruction. It can draw a circle twice over if so desired. That ability provides the basis for generating the more difficult alphanumerics in response to a two byte instruction. Let us look at a couple of examples: The letter 'a' for instance, is drawn by plotting the first circle, starting at X=R and Y=0. Then continue to plot the second circle while the X output is inhibited, which of course will produce a straight, vertical line of length 2R. (See Fig: #6) The number 9 is produced in the same manner with the exception that the sign bit for the co-ordinate increment is always held negative for the second circle. The letter 'b', on the other hand, can be produced as a capital letter by forcing the Y co-ordinate output for the first circle to be always negative and its X output always positive, while for the second circle, the X output is always inhibited and the Y output always positive. See Fig: #7.

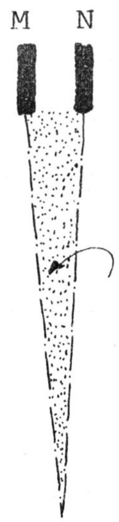
Type 2:

Level a-types of trace. This transfer function generates the instruction set required to control three different types of trace:-
a. solid line - b. no-trace line - c. mark-sapce line (an laternate sequence of solid and no-trace lines.) The control for solid line or no-trace, is actually only straight on-line pulses to the plotter and requires no processing. The mark-space line instruction however, does. The solid and no-trace lines are mandatory facilities for any plotting system, while the mark-space line is especially important for architectural design. The mark-space ratio would normally be adhered to by counting the increment instructions and at given counts, instructions will be generated to reverse the line media's up/down position. It is important for architectural drawings to have the mark-space length under program control. This programmable mark-space line facilitates the use of various architectural symbols. However, a more sophisticated and labour saving use for this mark-space line, is the ability to draw repetative architectural patterns, such as staggered masonary joints, with a single instruction.

Level b-hatching patterns. These transfer functions generate the instruction sets required for such tasks as automatic cross hatching required (e.g. brick or block walls) on architectural drawings. This is accomplished through the mark-space facility, while the direction of line is controlled by a 'circle mutation' instruction. The boundaries of the surface for such cross hatching are controlled through the counters for the 'sloping straight line' transfer function, which records the line media's current position.

A brief outline of the possible uses of the plotter controller as a dynamic device in the design synthesis process.

We have seen in Fig: #5, how we can draw a circle as a rectangle. We also mentioned how, under cross hatching boundary conditions, the line-generator is used to correlate the current location of the pen media to other significant parameters. Thus we should be able to let the design synthesis system allow the plotting system to sketch, according to some philosophy and recognition of present patterns, and assess the outcome rather than pre-define all its moves. This would allow for much of the randomness hitherto exclusive to human thought. This would be similar to architects layouts and subsequent assessment of the sketch. Whether plotting systems are used in man-machine interface situations, or in machine-machine interface, they are beginning to break through as dynamic processes in their own right.



If Eye is within the shaded area it can resolve M and N as separate entities.

Angle A ≤ 1 minute of Arch.

Fig. #1

Fig. #2

Fig. #3

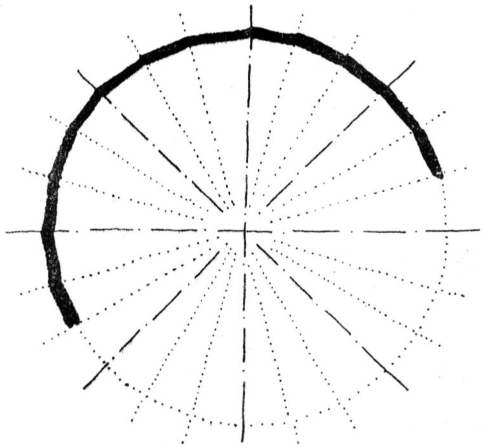


Fig. #4

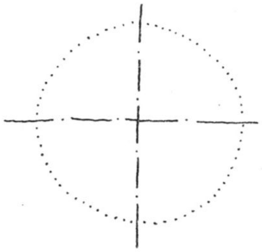


Fig. #5a

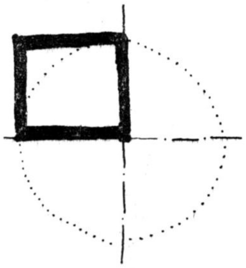


Fig. #5b

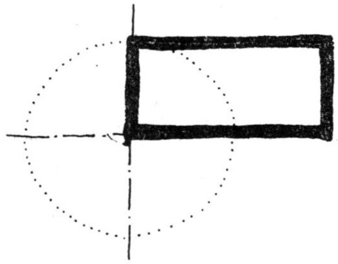


Fig. #5c

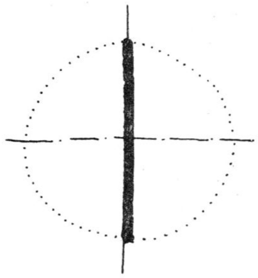


Fig. #5d

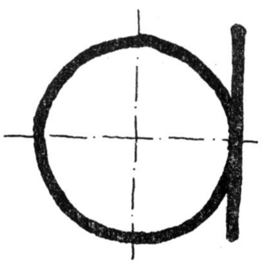


Fig. #6a

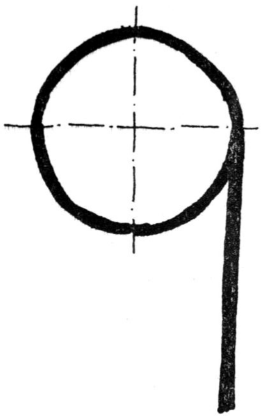


Fig. #6b

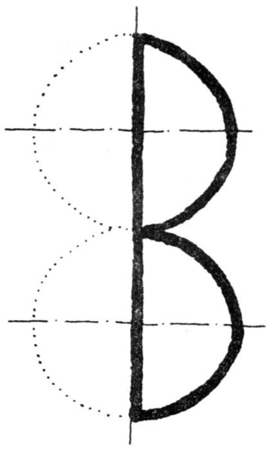


Fig. #7