Beam-Positioning Servo System for the Flying Spot Store

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This paper describes the cathode ray tube beam-positioning servo system essential to the accurate and reliable microsecond access to the photographic information in the flying spot store. The characteristics of both the basic servo loop and its components are discussed and several variations of the basic scheme are compared in relation to the system requirements.

I. INTRODUCTION

The flying spot store, a large, high-speed semipermanent memory, has been described by Hoover, Staehler and Ketchledge.[1] They have discussed the fundamental concepts and purposes of such a store and have clearly indicated that an essential feature of such a store is a servo-controlled positioning system. One form of such a positioning system has been described by them. This paper will consider to a greater extent the forms such systems may take and their relationship to the design objectives of the store.

1.1 *System Objectives*

Although the specific system environment for which the store designs were executed is a telephone switching system,[2] the use of the store in more general real-time data processes imposes very similar requirements. The use for which the highest speed of operation is required in the telephone switching application is for real-time operation from a stored program. Random access to tabular information, although needed rapidly, is not usually controlling because of the more infrequent reference. In the case of program information, two important access actions can be distinguished. The first and most common is a sequential access, stepping word by word along the program; the second is a random access occasioned by transfers to other parts of the program or to subprograms.

The first is referred to as an "advance" operation and the second as a "transfer" operation. Since the "advance" is more common in the systems we are concerned with, it is the most critical in speed. Thus, the objectives which are appropriate to the present positioning systems are to make advances as fast as possible and to allow two to three times longer for transfers where necessary. The speeds which are feasible with present systems result in an over-all advance cycle time in the range of 2.5 to 5.0 microseconds.

The size of the flying spot store array is, in the usual case, limited by the devices within the store rather than by the system. This limitation presently places the optimum raster size between 256 × 256 and 512 × 512.

1.2 *Background*

Realization of a useful flying spot store hinges to a great extent upon the development of an accurate beam-positioning system. The positioning problem is made difficult both by the large number of spot locations required in the array and by the difficulty of returning repeatedly over a period of several months to the desired spot locations with sufficient accuracy to obtain useful readout.

Development of the positioning system for the barrier grid store[3,4] has demonstrated the practicality of high-speed digital-to-analog converters for beam positioning where short-term accuracy is the primary requisite. Assuming a flying spot store array size of 256 × 256 and a positioning tolerance of ±0.1 of a spot spacing (to obtain a reasonable signal-to-noise ratio), the positioning accuracy required is ±0.04 per cent. To build a forward-acting positioning system with a ±0.04 per cent long-term cumulative stability in the digital-to-analog converter, deflection amplifier, cathode ray tube and associated power supplies is considered unrealistic. Hence, a closed-loop or feedback positioning system is mandatory.

The use of a servo positioning system offers additional advantages. In the servo positioning system, both the stored information and the edges used for servoing are mounted on a common frame. Thus, if a cathode ray tube is changed, rewriting of the information plates is not required. Moreover, the deflection error caused by stray magnetic fields and mechanical vibrations is nullified by the servo action.

1.3 *Organization of Paper*

This paper describes, first, the basic servo loop, its components and their characteristics; second, several positioning schemes making use of the basic servo philosophy; and last, a comparison of the various schemes relative to the system requirements.

II. BASIC SERVO LOOP

2.1 *Components of the Loop*

A block diagram of the basic servo system is shown in Fig. 1 for one of the two independent axes of the flying spot store. The comparator output is a function of the difference between the address recorded in binary form in the input register and the binary-type positioning information obtained from the optical beam encoder. The comparator output or outputs are connected to the integrating amplifier, which is a high-gain shaping amplifier used to establish the desired loop gain frequency characteristics. The deflection amplifier is a wideband power amplifier designed to drive the deflection plates of the cathode ray tube. The cathode ray tube beam is electrostatically deflected with no post-acceleration. The phosphor must have very fast rise and decay characteristics to meet system objectives. For the purposes of this paper, type P-16 will be assumed. Each photomultiplier tube output is amplified and buffered by its associated amplifier before being fed to the comparator

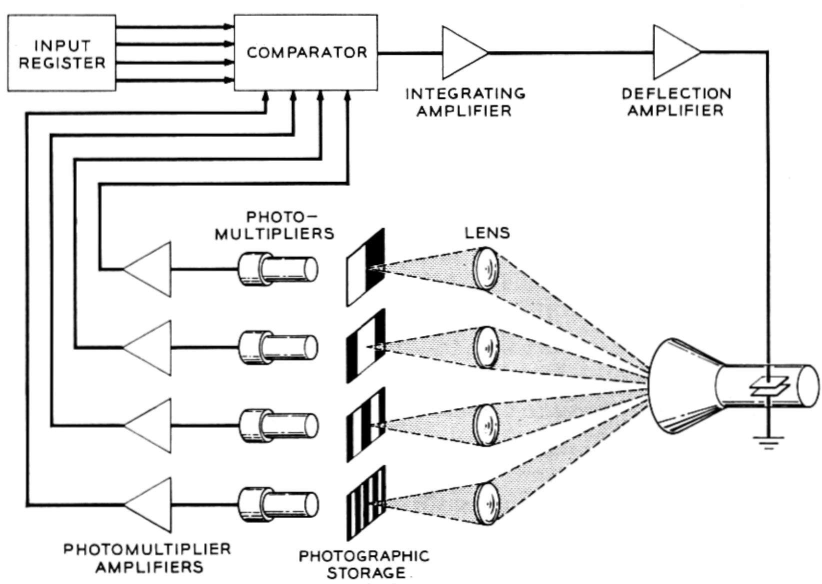

Fig. 1 — Block diagram of basic servo loop.

TABLE I — TRANSIT-TIME DELAY AND CUTOFF FREQUENCIES OF MAJOR LOOP COMPONENTS

Component	τ_d (mμsec)	F_{co} (mc)
Photomultiplier tube	60	—
Photomultiplier tube output circuit	—	0.4
Comparator	14	2.0
Integrating amplifier	10	10.0
Deflection amplifier	4	5.0
Cathode ray tube (P-16 phosphor)	11	2.5
Optical path	5	—
Connecting cables	12	—
Photomultiplier amplifier	3	5.0
Total	119	

Table I lists the components contributing appreciably to the true transit-time delay and the limiting cutoff frequencies of the various components. Most of the transit-time delay is inherent in the photomultiplier tube. This is to be expected, since, at each stage of a photomultiplier tube, the electrons are emitted with very low energies and are accelerated by only 100 to 150 volts per stage. The photomultiplier output circuit is responsible for the lowest cutoff frequency in the servo loop. This output response is limited by the amount of current that can be obtained from the photomultiplier anode consistent with a reasonable life expectancy.

2.2 *Servo Loop Characteristics*

The maximum crossover frequency that can be obtained is limited both by the loop transit time delay and by the cutoff frequencies of the loop components.

The minimum time delay obtainable, from Table I, is in the order of 100 millimicroseconds. This transit delay sets the maximum possible crossover frequency of the loop at 5 mc, corresponding to 180° phase shift. To be a bit more realistic, 90° should be allowed for the first-order integration characteristics of the shaping amplifier at crossover, plus at least a 30° phase margin to achieve reasonable stability. This leaves only 60° for transit delay phase, bringing the maximum frequency at gain crossover down to 1.7 mc.

The numerous frequency cutoffs listed impose a further practical limit to crossover frequency. Since the asymptotic slope is in the order of 48 db/octave above 10 mc, compensation beyond this point is not practical. Under this condition, the establishment of the crossover frequency requires an assessment of the expected gain variation to allow adequate gain margin.

Where possible, local feedback is provided to control the gain of each component of the loop. The cathode ray tube beam intensity is controlled by a feedback loop utilizing an optical channel and photomultiplier tube, along with a carrier amplifier to feed a correction signal to the cathode ray tube grid. This brightness stabilizer, as shown in Fig. 2, must have a response speed comparable to that of the positioning servo, since any variation in beam brightness affects the servo loop gain as well as the readout signal.

An intensity monitor circuit, using the same photomultiplier as the brightness stabilizer, is also shown in Fig. 2. This circuit provides a half-light reference signal for all the servo channels. It is the difference between this reference signal and the signal from the encoder channel that is used to position the beam. The purpose of this action is twofold. First, the intensity monitor prevents undesirable interactions between the position servo and the brightness stabilizer from occurring, since, with the monitor, the final beam position is independent of the beam brightness. Second, the intensity monitor provides additional correction for brightness changes that are beyond the speed or control range of the brightness stabilizer.

The photomultiplier tube gains are controlled by feedback techniques. In this case, a relatively slow sampled-data feedback system is sufficient, since the differential of gain with time is small.

All the amplifiers are gain-stabilized, either by a local feedback loop or by cathode degeneration. The integrating amplifier, shown in Fig. 3, is composed of a dc and an ac amplifier operating in parallel. The dc

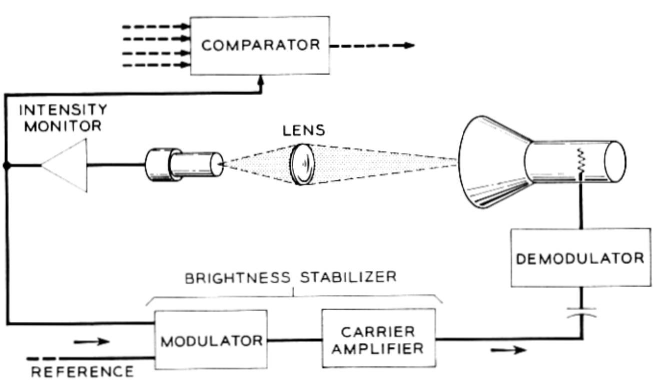

Fig. 2 — Block diagram of intensity monitor and brightness stabilizer.

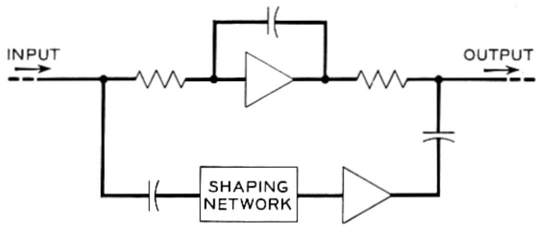

Fig. 3 — Block diagram of integrating amplifier.

section is a high-gain operational-type amplifier, while the ac section is a single-stage, low-gain shaping amplifier stabilized by cathode feedback.

Unfortunately, the optical section of the servo loop contributes three basic types of variations in gain which cannot be stabilized by feedback. Fig. 4 shows a typical crossover characteristic, along with an ideal crossover characteristic. The curves shown plot the luminous energy received on a photomultiplier tube face as a beam is passed over a servo edge. Since the spot on the phosphor has essentially a normal distribution in both axes, the crossover characteristic has a cumulative normal distribution. The slope of this characteristic curve determines the encoder gain and, thus, the loop gain. Since the servo tends to position the beam so that it is half hidden by the edge, it is observed that the servo loop gain is highest when the beam is settled in position. This gain is about 1.6 times the gain corresponding to the ideal crossover characteristic.

Variations in focus also vary the loop gain. This variation is a compounding of the focus obtained on the phosphor with that obtained by the lens. Both of these vary with beam position and may together con-

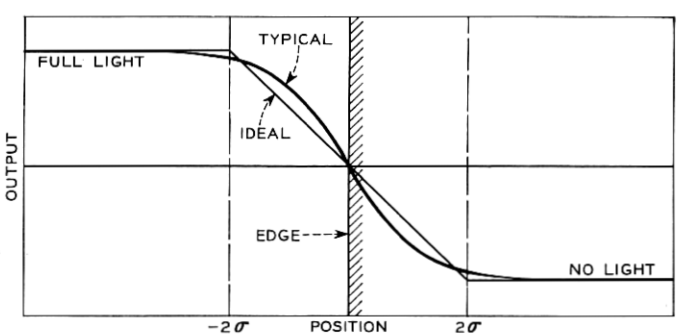

Fig. 4 — Optical encoder crossover characteristics.

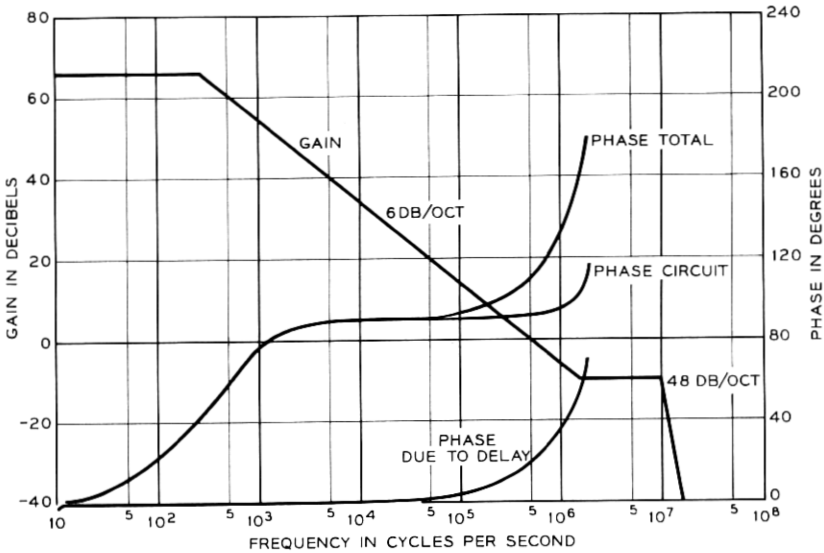

Fig. 5 — Open loop phase and gain vs. frequency.

tribute a variation of ±20 per cent to the loop gain. The light intensity varies across the field in the off-axis optical channels and causes an additional ±10 per cent variation in the loop gain.[5]

To provide for the expected gain variations, a design gain margin of 10 db is required. Fig. 5 shows curves of phase and asymptotic gain versus frequency that represent the optimum frequency crossover consistent with the findings of the previous sections.

It should be noted that a phase margin of 30° or better is maintained up to about 1.3 mc. Thus, system stability is assured, even with the gain variations discussed above. The crossover frequency shown is for the ideal optical crossover characteristic of Fig. 4. The difference between the typical and ideal crossover characteristic is absorbed as part of the gain margin.

A basic servo with these characteristics forms the basis for the beam positioning systems to be discussed next.

III. BEAM SERVO POSITIONING SYSTEMS

All the positioning systems which have been studied utilize either the sign-only, the approximate proportional or the true proportional comparator discussed in detail by Ketchledge[6] and Nesenbergs and Mowery.[7] The binary-Gray version of each of the above comparators is used to

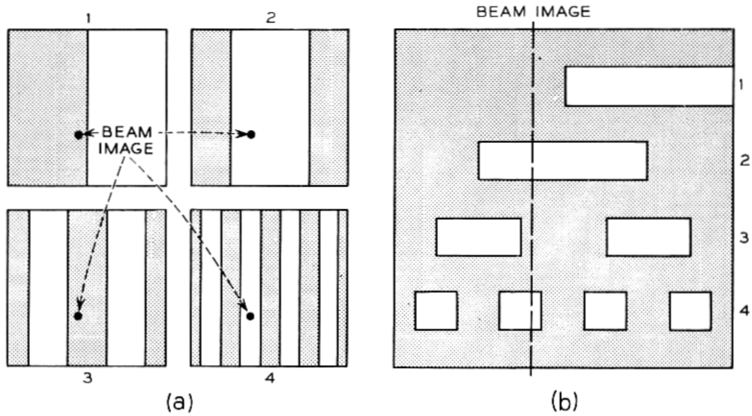

Fig. 6 — Gray code plates (a) for four channels of encoder, with (b) diagrammatic representation.

avoid the transition problem inherent in encoding analog information with a binary code plate system.

The Gray code plates shown in Fig. 6(a) are representative of the servo plates used in the four most significant digits of each axis of the beam position encoder. Fig. 6(b) shows diagramatically the relative positions of the servo edges contained on the plates of Fig. 6(a).

In the following paragraphs the characteristics of positioning systems making use of the above comparators will be discussed. The digital-to-analog converters utilized in some of the systems are similar to those in the barrier grid store that are described by Ault[3] in this issue.

The system response data quoted in the following sections were obtained initially from measurements made by simulating the system on an analog computer and later from measurements made on a series of laboratory models.

In the following sections note that the times indicated for various sizes of jumps are beam-positioning times that include settling but do not include other portions of the cycle necessary to obtain a complete readout.

3.1 *Sign-Only Servo*

The sign-only servo is one in which the magnitude of the error signal is developed by a sign-only comparator and is a linear function of the true error for small errors and a constant for larger errors. This results in a velocity-limited or saturated servo system.

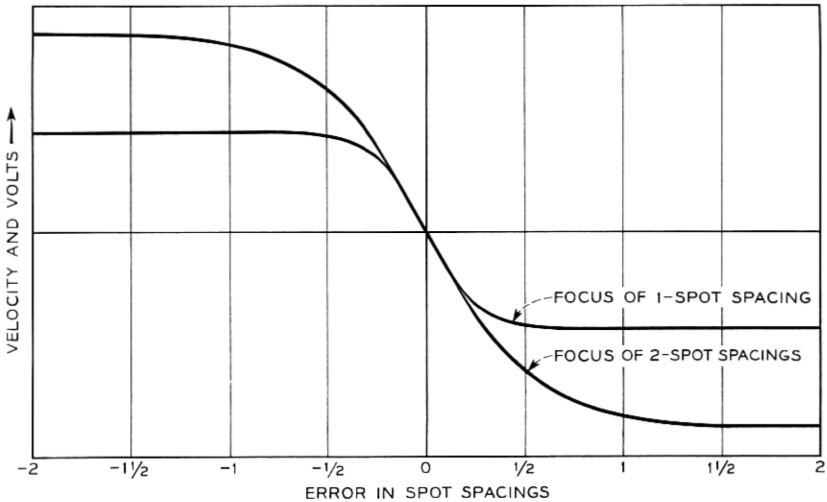

Fig. 7 — Effect of focus on optical crossover characteristic.

The extent of the linear range determines the magnitude of the drive and, thus, the slewing velocity outside the linear range. Fig. 7 shows plots of servo error signal versus spot displacement for two conditions of focus. The maximum slope is held constant for each curve, since the loop gain is a function of this slope, as discussed in Section 2.2. The maximum linear range obtainable with a conventional Gray code plate is reached at ± 1 spot spacing. This can be achieved by defocusing the optics of the servo channels so that the diameter of the light beam falling on the encoder occupies 2 spot spaces. Since the bars and windows of the least significant digit are each 2 spot spacings wide, this is the largest spot that can be used without reducing the drive signal. Obviously, if a tighter focus is used, the linear range is reduced; consequently, the velocity in the saturated region is likewise reduced.

Unfortunately, as the beam is defocused the optical gain is decreased, thus requiring an increase in the gain of one of the amplifiers contained in the loop. Also, the signal-to-noise ratio is degraded as the focus is degraded. This results because the main source of noise is the photomultiplier tube, and the additional gain needed to counteract the gain lost by defocusing must be supplied between the photomultiplier tube and the deflection plates.

The effect of light variations across the field on signal-to-noise ratio is also accented by defocusing the beam on the encoder plates. Consider an off-axis channel where variations in the light intensity may be ± 10

per cent. When the beam intensity in this channel is down 10 per cent, approximately 55 per cent of the beam must be exposed over the servo edge to balance the signal from the intensity monitor channel. It follows that, with a defocused beam, a larger shift in the position of beam center is required to obtain 55 per cent of the beam over the servo edge. The result is a crowding of some of the rows and columns in the matrix. A small amount of crowding is tolerable, since crowding is a physical constant of the system and would be present both when the storage plates are written and also when they are interrogated. Severe crowding, however, may result in the partial overlapping of spot locations, resulting in a degraded signal-to-noise ratio.

A balance must be made between the obtainable signal-to-noise ratios as a function of focus and the slewing speed. It is generally felt that defocusing the beam in the servo channel so that the $\pm 2\sigma$ limits of the beam occupy one spot spacing results in the best compromise performance. The resulting slewing speed is 1.5 spots per microsecond. When operation is at the maximum defocusing of 2 spot spacings the slewing speed can be increased to 3 spots per microsecond. The slower speed resulting from the tighter focus will be assumed in calculating beam-positioning times in this paper.

The time required to reposition the beam one spot spacing is roughly 1.2 microseconds, 0.8 microsecond of this being the settling time. The settling time is defined as the time required for the beam to settle within 0.1 of a spot diameter, starting from the time the beam enters the linear region (± 0.5 spot). On long jumps, the positioning time is primarily the time spent in slewing the beam. On a 100-spot jump, 67 microseconds are required to move the beam to within 0.5 spot and, again, an additional 0.8 microsecond being settling time.

The logic for sign-only servo comparison is relatively simple and, with the exception of the "exclusive or" function, easy to implement. The "exclusive or" is complicated because it must transmit the analog signal obtained from the encoder without appreciable distortion. Fig. 8 is a vacuum tube version of one digit of the sign-only servo comparator.

Since each channel of the servo system has at least one servo edge, each channel should have high-quality optics to prevent bowing of the rows and columns of the array due to light variations across the field. The least variation in light will occur in those channels located on or near the optical axis of the cathode ray tube. These channels are used, therefore, for the reference channel (intensity monitor) and the least significant digit servo channels. Since the two least significant digit channels (one for each axis) determine the location of every other row

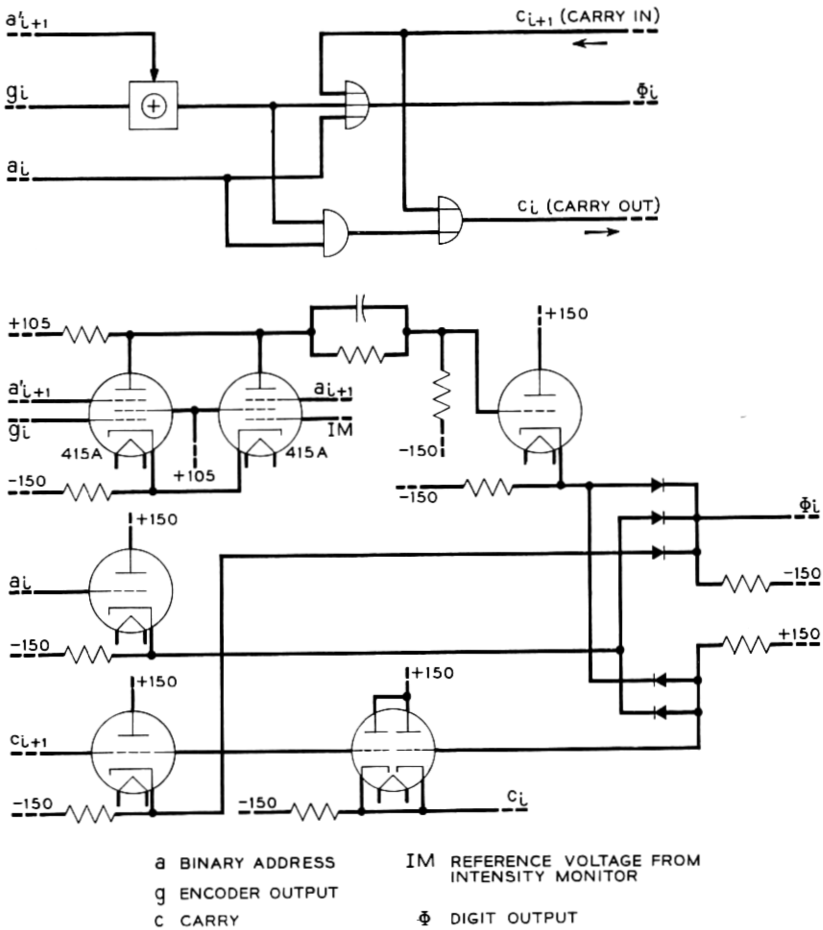

Fig. 8 — One digit of sign-only servo comparator logic.

and column in the array, they will be located near their ideal locations, allowing more latitude for the bowing in the remaining rows and columns.

3.2 *Sign-Only Servo Plus Digital-to-Analog Converter* (*DAC*)

In order to overcome the long positioning times required on long jumps with a sign-only servo, a DAC may be utilized as in Fig. 9. In this application, the DAC is used to rapidly position the beam as close as possible to the desired location, and the sign-only servo is used to correct any DAC error and establish the final location of the beam.

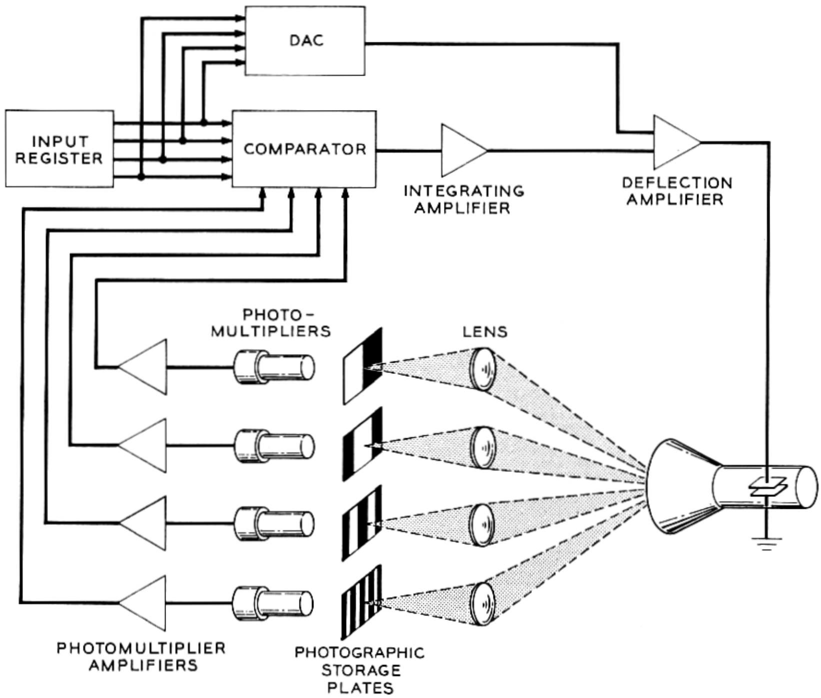

Fig. 9 — Block diagram of servo loop with DAC.

The DAC used in this application should have a sufficiently fast rise time (on the order of 90 millimicroseconds) so that its output will have arrived at its final value before the integrating characteristic of the servo loop has had time to accumulate a deflection signal that later must be integrated out to arrive at the desired location. This situation can be clarified by reference to Fig. 10.

The DAC is free of all dc drift-stability problems, since the servo will retain any DAC drift as a correction signal. Gain variations of the DAC, however, will cause the positioning system initially to overshoot or undershoot, which must be corrected by servo loop action. Distortions in the cathode ray tube such as "barrel" or "pincushion," as well as lack of orthogonality between the two deflection plate assemblies, also require the servo to make greater corrections, which increases the positioning time. These distortions are minimized by the advanced design techniques used in the development of the cathode ray tubes.

Use of the DAC tends to increase the time required to move a single spot location. The error is greatest when the address is changed from

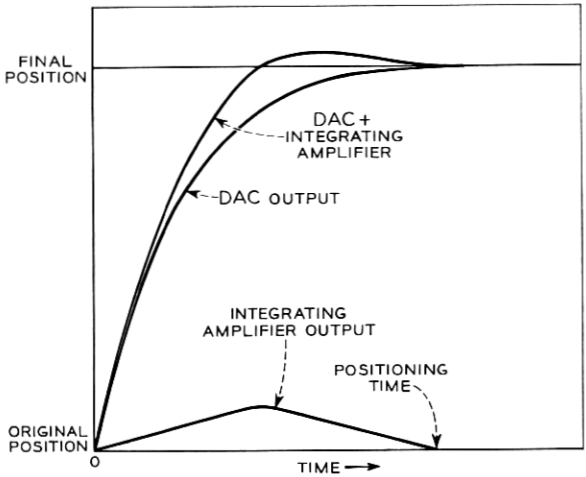

Fig. 10 — Effect of DAC rise time on positioning time.

0111...1 to 1000...0. Here a jump of only one spot position is called for, but the condition on every DAC input is reversed. The error that may result is controlled almost entirely by the accuracy of the resistors in the weighting network. It appears reasonable to expect that the worst error that can occur due to this effect can be held to 0.4 per cent of the raster's dimensions. Thus, for a 256 × 256 array, the worst error in adding one across the center of the array is one spot. That is, the output of the DAC either would not change or it would give an output corresponding to a 2-spot jump. This will increase the positioning time necessary to add one by 0.2 microsecond over the time required by the sign-only servo to position the beam. On the same size array, a large jump requires a worst time of 2.7 microseconds (0.6 DAC, 1.3 correction, 0.8 settling time). For larger arrays, correspondingly larger times are required.

Thus, by the addition of a DAC unit around the comparator, we have greatly decreased the time required for random beam positioning and only slightly affected the time required to add one.

3.3 *Approximate Proportional Servo System*

The approximate proportional servo using the corresponding binary-Gray comparator is a somewhat more elegant positioning system and, as might be expected, it is more complicated and costly. Basically, this system produces a nonlinear error signal that is bounded within

±6 db of the true proportional error signal. As with sign-only servo, the error is linear when the displacement is within ±0.5 spot.

Assuming a crossover frequency of 500 kc, as in Fig. 5, and a 256 × 256 raster array, the theoretical time required to reposition 256 spots is about 11 microseconds. The time required to move one spot location is the same as that required by the sign-only servo, approximately 1.2 microseconds.

The approximate proportional servo introduces two new problems. The first is a result of the large weighting factors which must be used on the outputs of the more significant digits of the comparator. The most significant digit channel of an eight-channel comparator would carry a weighting factor of 128, relative to 1 for the least significant digit channel. This high factor demands an extremely high signal-to-noise ratio to obtain a sufficiently low probability of a noise pulse occurring that would correspond to a half light condition. If such a pulse should occur in a digit with a high weighting factor, the resulting drive would temporarily displace the beam from its desired location. Because of this weighting problem, it is difficult to think of an approximate proportional servo with weighting factors much greater than 10. Thus, this system would be relatively slow on long jumps. Here again, the approximate proportional system could use a DAC system with the faster correction inherent in the approximate proportional servo.

A second problem results from the difficulty of maintaining dc stability and short transit time in the more complicated logic. The comparator output signal is always derived from the least significant digit channel (the only channel with unity weight) when the beam is settled in position, regardless of which channel receives the half light information as its input. Thus, the servo signal may enter the comparator's most significant digit input, proceed down the carry string (path) to the least significant channel and thence go to the output. The long transit time will appreciably increase the loop transit time, resulting in a lower servo speed. Moreover, the dc stability expected from this form of logic is not compatible with system reliability requirements. The latter problem is alleviated by a modified system discussed in Section 3.5.

3.4 *True Proportional Servo System*

The true proportional servo will not be discussed in detail. Although it provides a reduction in the random access time by a factor of about 1.5, its logic is somewhat more complicated and has the same inherent problems as the approximate proportional servo and, thus, the same limitations.

3.5 *Minimization of Number of Transmission (Linear) Channels Required*

In the previous articles,[1,6,7] and up to this point in this paper, each logical channel of the encoder and comparator had to be designed to handle linear positioning information, since the servo edges in each channel were used for locking the beam. The carry strings in the approximate and exact proportion comparator must also be linear. In order to overcome these and other similar problems, it is desirable to minimize the number of channels required to transmit the servo edge characteristics. This removes the linear design requirement from the remaining channels, which can now be concerned solely with logical selection of the desired edge and not with linear transmission.

3.5.1 *A Double Quantizing Channel System*

One scheme for implementing this minimization uses a coding scheme as shown in Fig. 11. Here, the least significant digit is displaced one-half spot spacing to the left and an additional least significant digit is placed one-half spot spacing to the right of the normal location. Only the edges in these two quantizing channels define the desired location, and thus they are the only edge characteristics transmitted for servoing. The rest of the channels are used only to create the direction of drive and therefore can use switching-type logic, which is characterized as two-state logic with inherent regeneration of the levels at each stage. Only speed and logical requirements are imposed on the transition between states. A diagram for a sign-only servo comparator for this system is shown in Fig. 12. Similar logic changes can be made for the proportional positioning systems.

At a focus corresponding to one spot spacing this system gives a

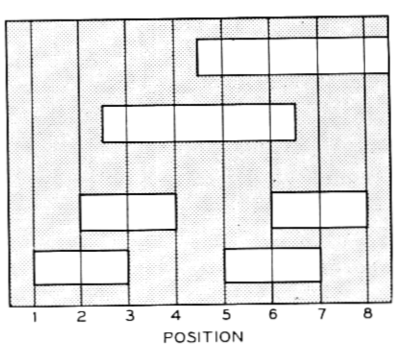

Fig. 11 — Diagrammatic representation of code plates for double-channel quantizing scheme.

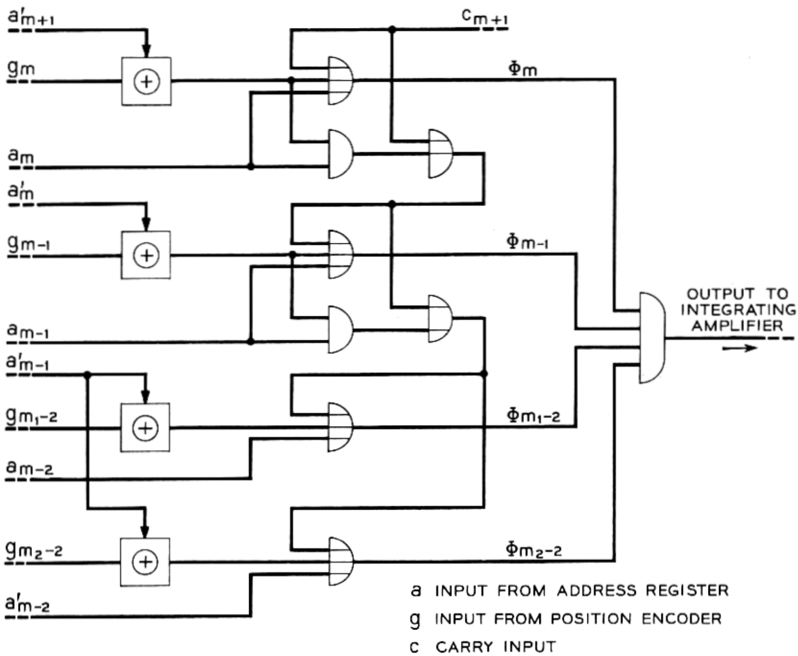

Fig. 12 — Comparator logic for a double quantizing channel system.

speed behavior identical to the normal coding system described in Section 3.1. However, as the focus is degraded, this system suffers a slight degradation in speed, which does not exceed 5 per cent at a focus corresponding to two spot spacing.

This scheme, at the cost of one servo channel, offers the following improvements:

i. A higher signal-to-noise ratio can be realized, since the two linear channels can be placed in preferred optical locations where the variations of focus and light across the field are small.

ii. The number of adjusting controls is greatly reduced, since the switching channels require no adjustments during alignment.

iii. The transit time of the comparator carry string does not affect the servo response time.

iv. The dc stability problems inherent in linear dc logic are removed by the use of switching logic.

3.5.2 *A Single Quantizing Channel System*

Another scheme for implementing the minimization also utilizes an additional channel. This extra channel corresponds to the next significant

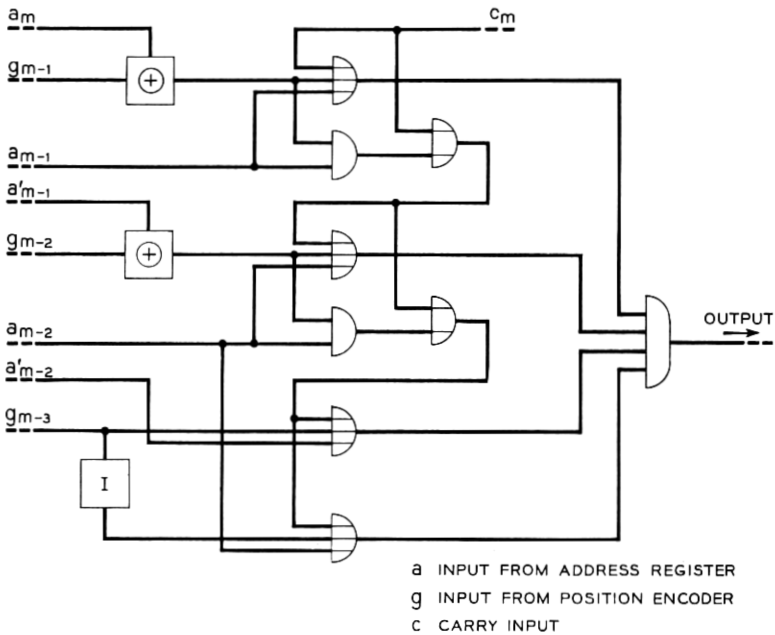

Fig. 13 — Comparator logic for a single quantizing channel system.

digit lower than the conventional least significant digit and contains an edge half-way between each edge of the conventional channels. With this system, only the edge characteristics in the single quantizing channel are transmitted to determine the final beam location. Fig. 13 shows the logic required for a sign-only servo comparator as modified to accommodate this scheme. An example of the simplification which was sought from this philosophy can be seen here. The only stage which must transmit servo information (the last stage) no longer requires an explicit "exclusive or" logical function, and the problem of designing this logic circuit to strict transmission requirements has disappeared. The "exclusive or" circuits in the higher stages are also made simpler by the removal of their transmission requirements.

This scheme has only one linear or transmission channel per axis, with even more simplification of the optical requirements and the adjustments. Greater reliability is maintained, since there are fewer components that can affect the beam position.

The positioning speed using this scheme is the same as that of the previous scheme when the beam is focused to one spot spacing on the encoder and is somewhat less than the previous encoder for larger spot sizes.

Table II — System Positioning Times

Size of Array	256 x 256			512 x 512		
Jump Length (Spots)	1	25	256	1	25	512
System	Time in microseconds					
Sign-only servo	1.2	17.5	172	1.2	17.5	342
Sign-only servo plus DAC	1.4	1.7	2.7	2.3	2.5	4.7
Approximate proportional servo	1.2	8.2	11.2	1.2	8.2	12.1
Approximate proportional servo, with weighting factor limited to 10	1.2	8.3	24	1.2	8.3	41
Approximate proportional servo, with weighting factor = 10, plus DAC	1.4	1.7	2.7	2.3	2.5	4.5
Exact proportional servo	1.2	4.5	6.5	1.2	4.5	7.0
Exact proportional servo, weighting factor = 10	1.2	5.0	21	1.2	5.0	38
Exact propo tional servo, weighting factor = 10. plus DAC	1.4	1.7	2.3	1.9	2.2	4.1

IV. COMPARISON OF SYSTEMS

Table II lists the longest positioning times that may be required for the various positioning systems as a function of jump distance and raster size. Reference to the table bears out the necessity of using a DAC to obtain a random-access time consistent with the design objectives, regardless of the comparator employed. The proportional schemes with DAC are faster on long jumps than with the sign-only plus DAC system, but their use may be unwarranted in view of the increased complexity of the proportional systems.

On an advance type of operation the DAC tends to degrade the positioning time, particularly on the larger raster size. This degradation is caused when digits of high significance are changed in the advance operation, the worst case occurring when crossing the center of the array, as discussed in Section 3.2. To circumvent this problem, the DAC input circuitry may be modified as shown in Fig. 14.

The modification of Fig. 14(a) reduces the worst possible error of the DAC by a factor of two, resulting in an improved advance time. In fact, this modification reduces the advance times listed for systems using a DAC on a 512 × 512 spot array so that they are identical to the times listed for a 256 × 256 spot array. Fig. 14(b) carries the modification one step further, resulting in a reduction of the worst possible error by a factor of four. With this modification, the advance positioning times for systems utilizing the DAC will be very nearly the same as those without the DAC. Thus, the time required to advance is essentially the same, regardless of the positioning system employed. This

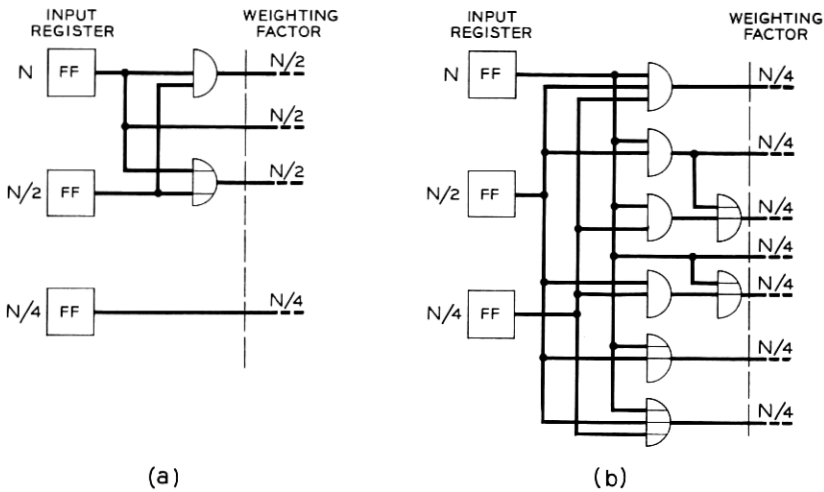

Fig. 14 — DAC input improved by (a) single-stage and (b) dual stage logic

factor accentuates the importance of basic servo loop component characteristics, as it is these components that will determine the advance time, rather than the positioning system.

Since the servo loop components play such a major role in determining the positioning time, it may be worthwhile to review the characteristics of some of the major components listed in Section 2.1.

Instead of utilizing a P-16 type phosphor, as previously assumed, other phosphors may be used because of their higher conversion efficiency or longer life. To date, no phosphor is available with rise and decay characteristics as fast as the P-16 type, although phosphors approaching the P-16 speed and offering higher efficiency and longer life have been noted. Phosphor efficiency and speed are almost equally important, as both affect the signal-to-noise ratio and, thus, the allowable gain crossover frequency. The importance of phosphor life must be evaluated on a basis of system requirements and economic considerations.

The only other component that may be modified to appreciably improve the servo loop characteristics is the photomultiplier tube. The stability of the photomultiplier dynodes may be improved so that a higher anode current may be utilized while a reasonable life is maintained. Also, changes in the structural design might result in a lowering of the electronic transit time in the photomultiplier, with a corresponding improvement in servo characteristics.

No ultimate servo loop characteristic can be given, as removing the limitations from any component increases the importance of the limitations of the other loop components, which may, in turn, be improved by further research.

V. CONCLUSION

Several systems making use of the basic servo loop characteristics have been discussed. It has been shown that the advance positioning time is primarily a function of the basic servo loop characteristics rather than the comparator system that is used. The random-access positioning time, on the other hand, depends considerably on the positioning system employed, although the servo loop and DAC characteristics are important factors.

To meet the system objectives, where the advance time is of greater importance and the transfer time is of lesser importance, the sign-only servo comparator plus DAC utilizing quantizing channels represents the best positioning system choice, because of its relative circuit simplicity and higher reliability. For different system requirements, where random-access time is critical, an approximate or true proportional comparator with DAC utilizing quantizing channels may be provided. The true proportional comparator, due to its considerably greater complexity, is justified only under the most severe system requirements, and where basic loop components have been used to their maximum capabilities.

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