14TH CONGRESS OF THE INTERNATIONAL
SOCIETY OF PHOTOGRAMMETRY

Hamburg, Federal Republic of Germany, 1980.

Commission: II

Working Group: II/4

Presented Paper

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SCANNING CATHODE RAY TUBE SYSTEMS FOR THE CONTROL OF PHOTOREPRODUCTIONS--A TECHNOLOGY REVIEW

ABSTRACT

This paper reviews the development of technology for optimizing the reproduction of aerial and other photography by the use of scanning-type photo printing systems.

The basic method of controlling exposure level and detail contrast in a reproduction, by means of an unsharp luminous mask generated by a scanning printing light source, was devised several decades ago and has reached a high state of development.

New research - particularly in the areas of automatic exposure prediction and more efficient operation of the cathode ray tube light source - will make it possible to expose some of the relatively insensitive reproduction materials, such as dry silver, electrophotographic film and the slower color emulsions, at rates which are significantly faster than heretofore, and should be of interest to all who are involved in the reproduction phase of photogrammetry.

SCANNING CATHODE RAY TUBE SYSTEMS
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A TECHNOLOGY REVIEW.

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I. THE AERIAL PHOTOGRAPHY REPRODUCTION PROBLEM

Photointerpreters, photogrammetrists, photographers, and photo technicians are frequently faced with a variety of problems when attempting to reproduce images, taken by aerial photography, with maximum information content and fidelity. The defects to be contended with include camera lens vignetting, sun angle effects, nonuniform exposures, and extremes of scene contrast. These disturbances result in great difficulty when attempting to match prints during the assembly of photo-mosaics, for example, and when attempting to reproduce all of the information contained in an original negative.

Traditional methods of overcoming reproduction non-uniformities on a scene by scene basis include the use of multi-light printers, unsharp masks and tissue overlays, and the process of hand "dodging" or "harmonization" to hold back printing light from the less dense regions of the image, thereby locally reducing reproduction densities and allowing the denser areas of the negative to contribute more significantly to the overall contrast of the reproduction. Unfortunately, considerable skill is required in making such reproductions because every negative is essentially unique and may require a somewhat different printing technique than its predecessor, resulting in slow and costly progress since frequent reprinting may be needed. Furthermore, when using manual methods of correction in a batch process, the ever-present system variables tend to prevent the technician from producing matching first and last prints, even from the same negative. Finally, because it is essentially impossible to manually modify the print exposure over small areas (say, less than 1 cm. in size) only the gross contrast of the reproduction can be influenced, leaving the detail contrast uncorrected.

II. BASIC ELECTRONIC PRINTING SYSTEM CONCEPTS

Faced with the foregoing problems, photographic workers in different parts of the World reached remarkably similar conclusions at about the same time, principally to the effect that the reproduction process could be greatly simplified and stabilized by the application of two technological developments which were then relatively new, namely:

a. the making of a photoprinting exposure on a point-by-point basis, using a small, intense spot of light deflected in raster fashion over the entire surface of the negative to be reproduced, and

b. photoelectrically monitoring and dynamically controlling the printing exposure after the light spot intensity has been modulated by the image densities present in the negative.

These rather simple techniques, when suitably combined, have revolutionized the photoreproduction process because they make it possible, over areas as small as the size of the scanning spot, to change the effective exposure (I x T) at the image receiving surface in a fashion which is the inverse of the densities existing in the original negative, i.e., dense areas can receive increased exposure, while thin areas receive relatively less exposure, thereby reducing the contrast of the reproduction for all areas larger than the scanning spot.

III. PHOTOPRINTING BY CONTACT AND PROJECTION

The earliest commercially successful electronic contrast-controlling photoprinters, some of which are still in use, were built by LogEtronics Incorporated, of the U.S.A. They take the form of contact printers in which the camera negative and photosensitive printing material are held in intimate, emulsion-to-emulsion contact on a transparent printing stage (Fig. 1). The rastered exposing light derived from a scanning cathode ray tube (CRT) having a phosphor screen of suitable spectral emission and persistence characteristics, is optically projected through the printing stage to the reproduction material. Because most copying materials are not opaque, some of the exposing light is detectable from the base (non-emulsion) side of the combination by the use of a suitable photosensor, and is converted to a varying signal current representative of densities existing in the original negative. This signal current is d.c. amplified and applied as a negative feedback voltage to the CRT electron gun, to inversely control the instantaneous brightness of the scanning spot as it traverses all points in the negative. A simple manually-set timer governs the exposure level of the reproduction.

It is most important to note that in flying spot scanning printers the emulsion of the camera negative and the emulsion of the copying material are always directly coupled to each other, either by physical contact, or through the medium of an optical system of appropriate resolving power. The image is never dissected to a video form, and then reconstructed. Thus, resolution loss during the reproduction process is held to an absolute minimum. In addition, by reconfiguring the system slightly, it is possible to optically enlarge (Fig. 2A) or reduce (Fig. 2B) the scale of the reproduced image while retaining all of the benefits of automatic unsharp luminous masking or, as it is more commonly called, "dodging". In such systems a small amount of the image-modulated light required for sensing purposes can be diverted from the main optical path by the use of a partially-reflective pellicle inserted in the printing light beam, or by detecting the light reflected from, or transmitted through, the reproduction materials.

IV. PRINTING LIGHT SOURCE CHARACTERISTICS

An ideal light source for use in a scanning photoprinter would display all of the following characteristics:

a. Constant spot size, slightly larger than any grain present in the emulsion of the photography to be reproduced, but with the capability of being defocussed to provide about a 10mm diameter scanning spot;

b. Spectral emission adjustable to match the characteristics of the reproduction material;

c. extremely high contrast (1000:1) to enable accurate sensing of a 0-3.0 image density range;

d. rapid build-up and decay of light emission (1 microsecond or less);

e. high intrinsic brightness, to provide good signal to noise ratios and short exposure times;

f. ease of brightness modulation and beam deflection, and absence of spot size change with intensity variations;

g. long operating life without significant degradation;

h. small physical size and weight;

i. low cost, and minimal overall complexity.

A quarter century of experience has shown that, despite the ready availability of lasers, light-emitting matrices, gas discharge panels, and other exotic sources, the CRT remains pre-eminent as the light source of choice for use in electronic scanning printers. It is true that none of its characteristics exactly match the foregoing requirements, yet it does combine most of them into a single relatively inexpensive and easily adaptable package requiring only a modest amount of external electronic circuitry for its operation.

Further improvements are still desired in the persistence, spectral emission, electron/photon conversion efficiency, screen uniformity and burn-resistance properties of the phosphors, and in overall faceplate contrast, and these matters continue to receive the attention of major chemical suppliers and the CRT industry.

V. EXPOSURE CONTROL METHODS

Any photographic image can be considered to contain two information components: an average or "constant exposure" portion which, in electronic terms, is similar to the d.c. component of a video signal, and an alternating part containing the image detail. The d.c. component represents the exposure level for the midtone density of the reproduction which, when correctly treated in a scanning printer, enables us to speak of the printer as having "electronic exposure control." The a.c. component represents the information-bearing part of the image brightness range, which must be manipulated by the dodging system to make it fit the exposure acceptance range, from highlight to shadow, of the reproduction material. For dodging printers, the reproduced image density usually centers about the midtone density in the negative. This is particularly true for aerial photography, because all parts of the image are likely to have equal importance, and it is necessary to preserve all of the highlight and shadow detail in the reproduction.

In order to reproduce an acceptable image on a photographic emulsion two basic elements of information are required, namely: the emulsion speed, and the mid-tone density of the image to be reproduced. The emulsion speed is usually calibrated into the exposure system by means of an adjustable exposure index or exposure value control and, in the case of a CRT printer, the dependent variable may be:

a. a rectilinear single frame raster (Fig. 3A) wherein the number of scan lines is adjusted to produce the necessary basic exposure, or

b. a multiframe rectilinear raster wherein the exposure value is a function of the scan pitch in lines/cm multiplied by the number of frames constituting the exposure, or

c. a Lissajous-pattern raster, in a single frame (Fig. 3B) or multiframe (Fig. 3C) format.

The multiframe rectilinear exposure is now the method of choice in most electronic printers for three specific reasons:

1. the number of frames can easily be controlled through the use of a simple electronic counter;

2. multiframe exposures minimize electronic noise effects which could otherwise tend to produce bars, stripes, blotches, or the like in the reproduction;

3. rectilinear scans can produce a constant exposure level irrespective of raster area, whereas Lissajous-pattern exposures tend to vary inversely with scanned area, complicating the matter of exposure constancy versus format size.

VI. PRINTER MODULATION SYSTEMS

In Fig. 4A the oldest form of CRT dodging, by direct coupled intensity modulation, is compared with other block diagrams B, C, and D, which show more modern a.c. coupled intensity modulated (IM), velocity modulated (VM) and dwell-time modulated (DTM) systems. A point of particular interest with the a.c. coupled IM system shown (Fig. 4B) is the use of two photodetectors. The field of view of the integrating exposure control pick-up tube is "steerable," thereby allowing the operator to define the section of the image which will be monitored by photoelectric integration to determine the average exposure of the print. Furthermore, the feedback amplifier can then be a.c. coupled, enabling the CRT to operate at higher average brightness and thereby reduce exposure times. Obviously, such a scheme is practical only with a multiframe exposing system employing sufficient frames to allow the required fine control of exposure.

In the velocity modulation system (Fig. 4C) the CRT is operated at a constant brightness and the photodetector output signal modulates the horizontal axis deflection rate in such a way that the scanning spot moves relatively slowly in dense areas of the image to be reproduced, and more rapidly in the thin areas. A staircase generator is triggered at the ends of each scan line of the rectilinear raster to provide vertical axis deflection, and a blanking circuit prevents exposure during the vertical retrace.

Two important characteristics of the VM printing system are:

a. that it is an open-loop control in which the property sensed (spot brightness) is not the property which is being controlled (spot velocity), so that the system does not suffer from oscillation resulting from excessive phase shift in the negative feedback loop, as IM systems often do;

b. that constant beam current operation minimizes changes in CRT spectral emission when using a compound phosphor for the printing of color photography.

Dwell time modulation (Fig. 4D) is a special case of the VM system, in which the horizontal beam deflection circuit used for the CRT in VM is replaced by an integrating exposure control driven by signal currents received from the photodetector. The scanning spot is caused to move incrementally from point to point over all parts of the photography to be reproduced, and to dwell at each point for a sufficient period of time to expose the printing emulsion to the desired degree, i.e., the spot dwells for longer periods of time in dense areas of the original photography than it does in thin areas.

VII. PRINTER CONTROL BY PRESCANNING

A conclusion which may be drawn from the preceeding observations is that a true single-frame scanning printer, having separate exposure control and dodging functions based on the density distribution within the negative to be reproduced, cannot be constructed since it requires circuits having predictive capabilities. Thus, single-frame printers are either d.c. coupled or have no inherent exposure control. Some current printers employ single-frame variable dodging wherein if other than maximum dodging is required, the exposure control must be preset by the operator as a result of his visual preassessment of the negative to be reproduced.

As an improvement, the next generation of printers will contain automatic electronic prescanning circuits capable of rapidly and accurately determining the proper exposure level (density average) and contrast (density range) of a subject to be reproduced. The use of these abilities will make it practical to choose any one of several printer circuit configurations.

Those printers which expose in the shortest time all embody IM-VM or IM-DTM circuit combinations. As was mentioned earlier, dwell time modulation (DTM) can be considered as a special case of VM, and is so treated here. A block diagram of one new IM-VM combination, on which patents are pending, appears in Fig. 5, which differs from Figure 4C as a result of the inclusion of the blocks identified as "current replicator" and "d.c. coupled CRT beam current amplifier." The two outputs, I'_{pmt}, of the current replicator circuit are intended to be duplicates of the photomultiplier current I'_{pmt}. The requirement for current replication applies particularly to the horizontal control circuit, in order to ensure linearity of dodging. Moreover, although it is not a fundamental requirement, the beam current amplifier is designed to drive the CRT cathode, rather than its control grid, in order to further improve system linearity.

The factors which have led to the development of the new IM-VM concept include:

a. the emerging use of dry silver and non-silver emulsions, which require higher printing energy levels;

b. the need for shorter printing times with color reproduction materials;

c. the recognition that velocity modulation is a faster exposing method than intensity modulation only at low and medium densities;

d. the fact that a d.c. coupled IM system achieves its maximum brightness only in the densest areas of the negative being reproduced.

The tables which follow compare three types of printer circuitry with respect to printing speed. These are:

1. a d.c. coupled form of intensity modulation, only;

2. velocity modulation only, and

3. combined intensity/velocity modulation.

Note that the IM/VM system can be adjusted so that the IM and VM dodging circuits operate over the same density range simultaneously or sequentially, or over different parts of the range either simultaneously or separately. For pragmatic rather than theoretical reasons, the operating conditions shown in the charts which follow are defined to produce dodging in three distinct density ranges, namely:

a. VM only, for low densities;

b. combined IM/VM for mid-tone densities, and

c. VM only, for mid to high densities.

The total VM range under these conditions is 25:1 and the IM range is 4:1 yielding an overall dodging range of 100:1.

Table I illustrates the conditions prevailing for velocity modulation when the scan velocity is linearly related to the photodetector current, and density is varied over an 0.0-2.0 range (i.e., a transmission range of 100:1).

Table II illustrates density variations vs. CRT cathode current in a d.c. coupled IM printer, over an 0.0-2.0 density range, at a constant scan rate.

Table III shows the combined result of photodetector current, beam current, and scan velocity variations over an 0.0-2.0 density range.

Table IV provides a comparison of relative exposing speeds between the preceding three systems, under identical density conditions.

For the conditions specified, the printing speed for the IM/VM combination is found to be four times greater than for IM only, and 3.6 times greater than for VM only. As a further point, the IM/VM combination can never be slower than IM only, or VM only, for a given density, and typically is appreciably faster.

VIII. CONCLUSIONS

We have shown that scanning CRT photoprinters produce contrast-controlled image fields in which the dodging action is characterized by the generation of a luminous mask automatically superimposed upon the original subject matter to be reproduced.

The degree of mask unsharpness is normally a function of the relationship between the size of the scanning spot and the size of the detail to be reproduced, and the effect of the luminous mask is usually to reduce the gross image contrast (areas larger than the scanning spot) and thereby make possible the enhancement of detail contrast (areas smaller than the scanning spot) by the use of reproduction materials of higher contrast than could otherwise be accommodated.

A new generation of electronic circuits will facilitate the more efficient programming and control of scanning light sources, thereby yielding printing rates which are dramatically faster than heretofore. These developments will make it possible, for the first time, to expose relatively insensitive reproduction materials--such as dry silver and photoconductive--by contrast controlled electronic scanning at commercially acceptable rates, and will lead to entirely new applications and products.

Looking into the more distant future, it is certainly conceivable that laser technology, with its ability to provide micron-sized high energy scanning spots, may eventually yield relatively simple image dissecting and reproducing systems in which digitized data is manipulated by computers in ways which are significantly different from those now in use. However, there is little doubt that conventional photoreproduction methods and materials, such as have been discussed here, will be in widespread use for many years to come as a result of their fundamental simplicity and modest cost.

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TABLE 1

DENSITY	I_{PMT} (μA)	SCAN VELOCITY V_S (cm/sec.)
0.0	50.0	7600
0.1	39.7	6040
0.2	31.5	4800
0.3	25.0	3810
0.4	20.0	3030
0.5	15.8	2400
0.6	12.5	1910
0.7	10.0	1520
0.8	7.9	1200
0.9	6.3	960
1.0	5.0	760
1.1	3.9	604
1.2	3.1	480
1.3	2.5	381
1.4	2.0	303
1.5	1.5	240
1.6	1.2	191
1.7	1.0	152
1.8	0.7	120
1.9	0.6	96
2.0	0.5	76

Transparency density and idealized photomultiplier current variations vs. scan velocity (V_S), at a constant CRT cathode current of 200 microamperes, in a typical VM printer.

TABLE II

DENSITY	I_K (μA)
0.0	8.0
0.1	10.0
0.2	12.7
0.3	16.0
0.4	20.0
0.5	25.0
0.6	32.0
0.7	40.0
0.8	50.0
0.9	63.5
1.0	80.0
1.1	100.0
1.2	127.0
1.3	160.0
1.4	200.0
1.5	250.0
1.6	320.0
1.7	400.0
1.8	500.0
1.9	635.0
2.0	800.0

Transparency density and idealized CRT cathode current (I_K) variations, at a constant scan rate of 303 cm/sec. (the rate shown for a density of 1.4 in Table 1) in a typical d.c. coupled IM printer.

TABLE III

DENSITY	I_{PMT} (μA)	I_K (μA)	VELOCITY/V_S (cm./sec.)	MODE
0.0	50	200	7600	VM Only
0.1	39.7	200	6040	
0.2	31.5	200	4800	
0.3	25	200	3810	
0.4	24.5	250	3720	IM/VM
0.5	23.5	300	3500	
0.6	22.3	355	3380	
0.7	20.8	420	3160	
0.8	19.3	487	2930	
0.9	17.7	575	2690	
1.0	16	642	2430	
1.1	14.3	720	2170	
1.2	12.5	800	1900	
1.3	10	800	1520	VM Only
1.4	7.9	800	1200	
1.5	6.3	800	958	
1.6	5.0	800	760	
1.7	3.9	800	604	
1.8	3.1	800	480	
1.9	2.5	800	381	
2.0	2.0	800	303	

Comparison of changes in transparency density to idealized variations in photomultiplier current (I_{PMT}), CRT cathode current (I_K), and scan velocity (V_S) in a combined IM/VM printer.

TABLE IV

DENSITY	IM ONLY	VM ONLY	IM/VM
0.1	2.5 SEC	0.12 SEC	0.12 SEC
0.4	2.5	0.25	0.20
0.7	2.5	0.50	0.24
1.0	2.5	1.00	0.31
1.3	2.5	2.00	0.50
1.6	2.5	4.00	1.00
1.9	2.5	8.00	2.00
TOTAL TIME	17.5 SEC	15.87 SEC	4.38 SEC

Exposing Conditions: 420 Sequential scan lines, each 12.7cm long and with an 0.3mm line advance, to form a 12.7cm x 12.7cm raster.

Comparison of changes in exposure time required when reproducing a seven-segment transparent step tablet to matching densities by means of IM only, VM only, and combined IM/VM printing.

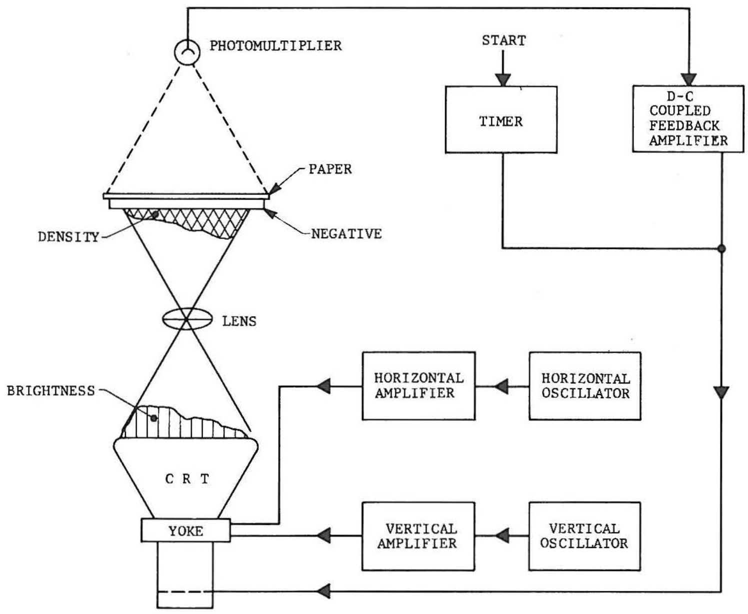


FIG. 1. INTENSITY MODULATION WITH D-C FEEDBACK.

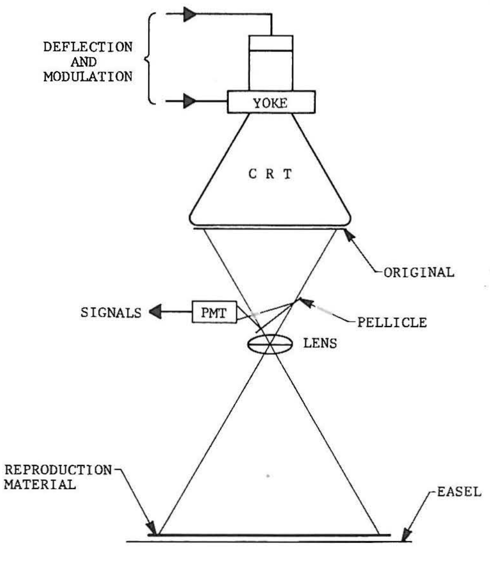


FIG. 2A. ENLARGEMENT.

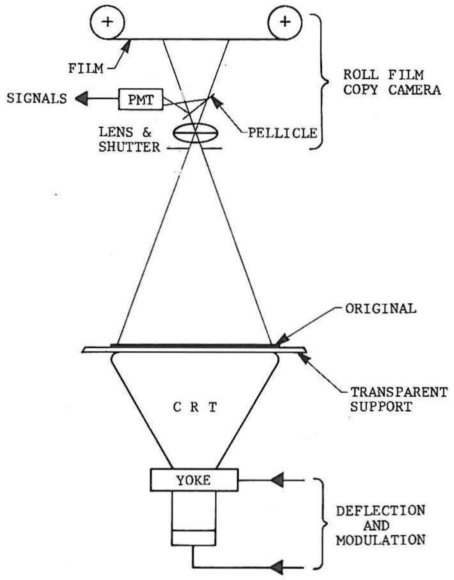
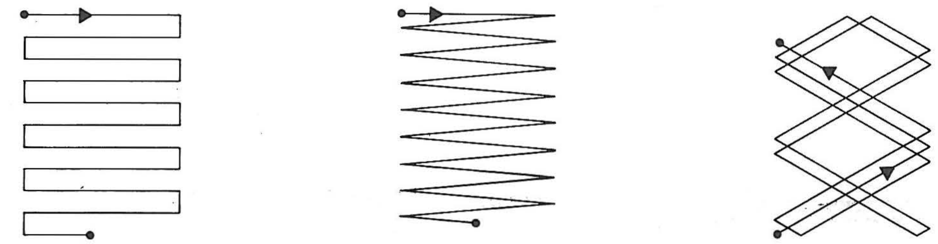


FIG. 2B. REDUCTION.

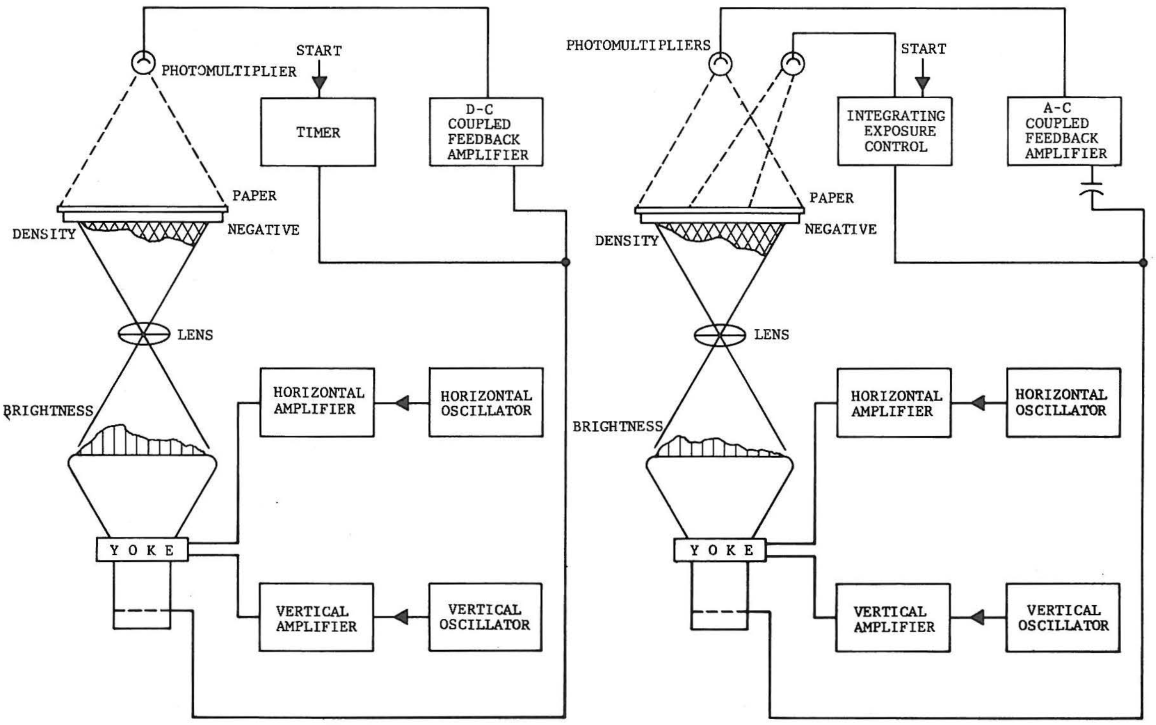


A. RECTILINEAR PATTERN (SINGLE OR MULTI-FRAME)

B. LISSAJOUS PATTERN (SINGLE FRAME)

C. LISSAJOUS PATTERN (MULTI-FRAME)

FIG. 3. TYPES OF RASTER SCANS

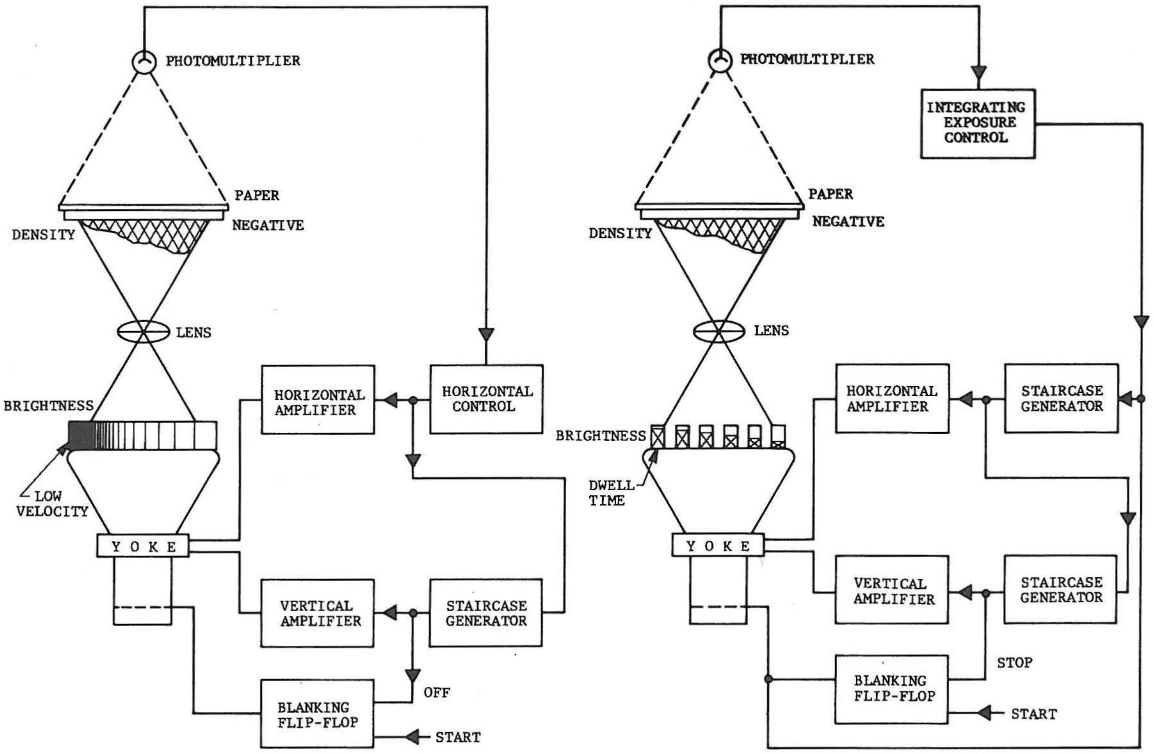


INTENSITY MODULATION WITH D-C FEEDBACK

A

INTENSITY MODULATION WITH A-C FEEDBACK

B



VELOCITY MODULATION

C

DWELL TIME MODULATION

D

FIG. 4. BLOCK DIAGRAMS-PRINTER CONFIGURATION

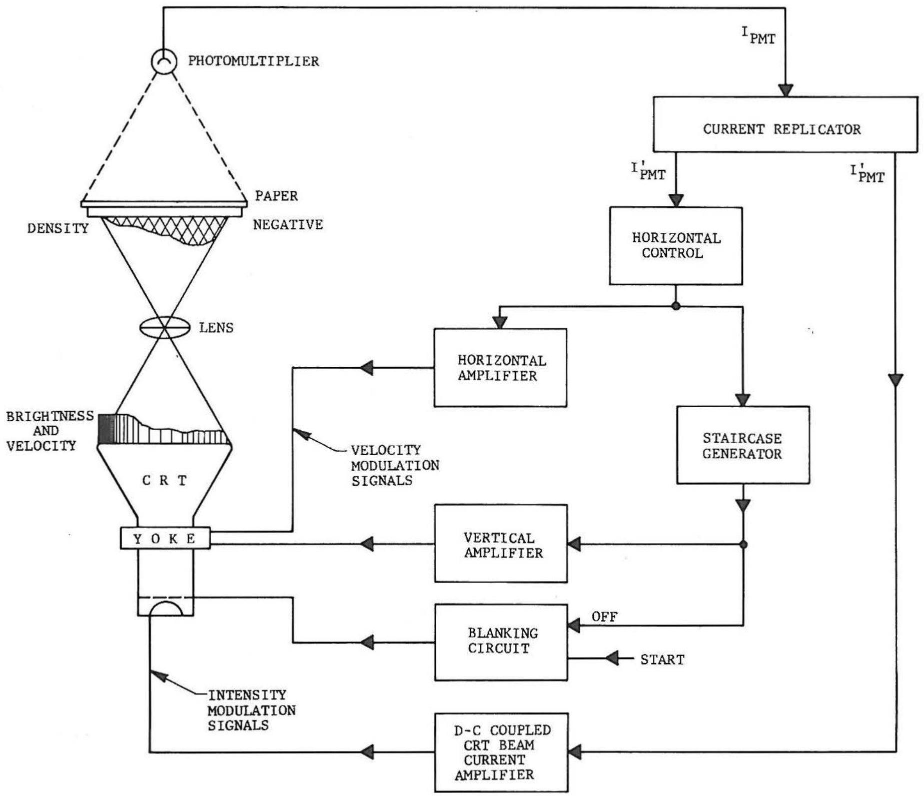


FIG. 5. NEW D-C COUPLED IM-VM PRINTER CONFIGURATION.