USC–EE REPORT #131T

STOP-SCAN EDGE DETECTION SYSTEMS OF TELEVISION BANDWIDTH REDUCTION

By

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June 1965

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SSD-TR-65-44

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INTERIM TECHNICAL REPORT NO. SSD-TR-65-44

June 1965

Space Systems Division
Air Force Systems Command
United States Air Force
Los Angeles, California 90045

Project No. 5218, Task No. 10

(Prepared under Contract No. AF 04(695)-537 by Department of Electrical Engineering, University of Southern California, Los Angeles, California; W. K. Pratt, Author)

FOREWORD

This report was prepared by the Department of Electrical Engineering of the University of Southern California under USAF Contract No. AF 04(695)-537. This contract was initiated under Project No. 5218 University Program, Task No. 10, "Aerospace Vehicle Detection and Tracking Systems". The work was administered under the direction of Space Systems Division, Air Force Systems Command with Captain R. D. Eaglet acting as project officer and technical support furnished through the TDPS Office of Aerospace Corporation.

ABSTRACT

A family of systems is developed to code television pictures such that the bandwidth, or time, required for transmission is reduced significantly compared to transmission by conventional pulse code modulation. The systems have application for spacecraft television communication where the reduced bandwidth enables a reduction in transmitted power. Data from optical detection and tracking sensors may be processed at a significantly increased rate with the systems. Also, for a fixed communications bandwidth, the television bandwidth reduction systems permit an increase in the number of television channels that can be relayed by an earth orbiting satellite or microwave relay station.

The major informational content of a television picture as judged by a human viewer lies in its outline, or edges, which occupy only a small area of the total picture. A bandwidth reduction is realized by transmitting video information suitably coded and time redistributed only at the edge positions in a picture. Edges are formed by subtracting the intensities of adjacent picture elements along a television line. If the difference signal exceeds a threshold value an edge exists. The position of each edge is coded as the number of elements scanned since the previous edge occurrence.

The time redistribution is performed by a stop-scan picture information gathering and display process at the coder and decoder eliminating the need for high speed buffer storage units. In the stop-scan process, camera scanning proceeds at a uniform rate; when an edge is detected, scanning is halted. At the next allowable edge transmission time, the video information is transmitted, and scanning resumes. The display of video information at the decoder follows an inverse stop-scan process.

In this report the psychophysical properties of image viewing related to television systems are investigated to determine the relationship between television design parameters and communications bandwidth. Information theoretic bounds of bandwidth reduction and the optimum selection of system parameters are established. Statistical image measurements are performed to determine the probability of occurrence of edges. The implementation of an operational prototype of the basic stop-scan edge detection system is described. Viewing tests are performed to verify the quality of pictures processed by the basic system.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF EXHIBITS

LIST OF TABLES

ACKNOWLEDGMENTS

The author wishes to acknowledge the advice and encouragement provided by the members of his guidance committee: Professors S. W. Golomb and A. L. Whiteman, and most particularly the chairman, Professor I. S. Reed. Professor R. B. McGhee is also thanked most gratefully for his suggestions and guidance. The support, encouragement, and motivation provided by Professor Z. A. Kaprielian throughout the author's graduate program is gratefully appreciated. Mr. C. C. Crain of Crain Electronics provided valuable assistance in the experimental portion of the research project.

This research was supported to a significant degree by the Space Systems Division of the United States Air Force under contract AF 04(695)-537. The author was the recipient of a Hughes Staff Doctoral Fellowship for the academic year 1964-1965. This generous assistance enabled the research to be performed on a full time basis.

The completion of this dissertation and the author's graduate studies is due in great part to the encouragement and forbearance of his wife. Her understanding and confidence will always be appreciated.

CHAPTER 1

INTRODUCTION

1.1 General Background

Television is becoming an increasingly important method of scientific and military communication in addition to its widespread use as an entertainment medium. In space applications television systems have become one of the key components of many missions. Military space surveillance systems use visible and infrared television cameras in many aerospace vehicle detection and identification applications. As commercial and military nets of communications satellites become operational, regular world-wide television transmission will become commonplace. In terms of commercial applications, television transmission is increasing rapidly over the world as new stations are being built. With this increase in the number of stations comes the growing requirement for the relaying of television between stations. Television is also finding growing use in many industrial applications such as the monitoring of industrial equipment. Finally, many military uses of television such as monitoring action on a battlefied are developing.

Perhaps the most significant problem encountered in transmitting television signals is that of the large bandwidth required for conventional quality television. This large bandwidth requirement results in heavy, high-power transmitting units for satellites and spacecraft; complex, expensive relay stations and coaxial cables; and a general overcrowding of the television transmission bands.

Many methods of television bandwidth reduction have been proposed, but few have been able to offer a sizeable bandwidth reduction without degrading picture quality or being impractical to implement. One method that appears to be relatively free of these disadvantages is the stop-scan edge detection system[1]. The basic stop-scan edge detection system offers potential bandwidth reductions of 4-6 over conventional television. A bandwidth reduction approaching a factor of 20 or more is possible when full utilization is made of extensions to the edge detection concept.

The implications of a reduction in television transmission bandwidth of the orders of magnitude mentioned above are extremely significant, for with the reduced bandwidths contemplated it will be possible to:

(1) transmit television pictures over much less expensive coaxial cables and relay stations, and in some instances

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[1] Appendix I contains the results of a survey and analysis of television bandwidth reduction systems.

over ordinary phone lines;

(2) reduce the weight requirements of the transmitter and associated power supply in a satellite or spacecraft transmitting television;

(3) decrease the overcrowding of the television transmission bands for relay satellites and relay stations.

1.2 Research Objectives

The objectives of this research project are the analysis, design, development, and implementation of television bandwidth reduction systems based upon the stop-scan edge detection concept[1]. The approach taken toward the fulfillment of these objectives is:

(1) conceptual development of a family of stop-scan edge detection bandwidth reduction systems;

(2) analysis of the systems supported by statistical picture measurements to determine their bandwidth reduction capability;

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[1] The term television is used here to denote video signal information sequentially obtained from a scanning type of sensor; and thus, includes not only real time television systems, but also slow scan television, and facsimile systems. Furthermore, the television signal may arise from any image forming sensor operating either in the visible or infrared frequency region with a multilevel grey scale of brightness, or simply a bilevel black and white brightness indication.

(3) implementation of the basic stop-scan edge detection system to demonstrate its feasibility;

(4) performance of viewing tests to evaluate the picture quality of the basic stop-scan edge detection system.

1.3 Organization of Dissertation

Chapter 1 is an introduction containing a discussion of the significance and objectives of the research project. The chapter closes with a summary of the organization of the dissertation, and an explanation of notational conventions employed.

Chapter 2 presents an explanation of the stop-scan edge detection concept of television bandwidth reduction which is the central core of the research effort. A summary description of the operation of typical edge detection systems is also included.

Chapter 3 discusses the psychophysical properties of image viewing as related to television systems. The connections between the viewing properties and design parameters which determine the bandwidth of television systems are delineated.

Chapter 4 is an information theoretic analysis of edge detection coding. The theoretical bounds of edge coding bandwidth compression are derived in the chapter and compared to the bandwidth reduction of practical edge coding methods.

Chapter 5 contains the results of measurements of the statistical properties of images. The measured probability of occurrence of edges is presented for edge detection coding.

Chapter 6 is an analysis to determine the optimum values for the system parameters of the edge detection systems. A section on the bandwidth compression factors and information rate capability of edge detection systems concludes the chapter.

Chapter 7 is devoted to the presentation of an implementation study of the basic stop-scan edge detection system. The study is supported by an experimental investigation of the system components and the actual construction of the complete basic system.

Chapter 8 presents the results of viewing tests of the basic stop-scan edge detection system. Photographs of scenes televised at a reduced bandwidth are included.

Chapter 9 summarizes the results of the dissertation. Extensions to the research are discussed.

The list of references following the text represents a nearly exhaustive bibliography of television bandwidth reduction techniques and related topics.

1.4 Notational Conventions

In the functional block diagrams, information flow is indicated by heavy lines. Light lines represent control functions.

A list of frequently used symbols is presented in the glossary.

CHAPTER 2

STOP-SCAN EDGE DETECTION SYSTEMS

The method of reducing television bandwidth that has been adopted for this research project is that of removing redundancy from a television signal by techniques based upon the edge detection concept. The non-redundant picture information that remains is uniformly distributed over the original transmission time period by the stop-scan video signal gathering process to achieve a communication bandwidth reduction.

2.1 Principle of Stop-Scan Edge Detection

Experimental evidence [67] indicates that a viewer perceives mainly the outline of objects. The eye is relatively insensitive to the absolute brightness of elements of a picture and judges relative brightness with respect to the surrounding portions of a scene. These properties of sight indicate that the major informational content of a picture lies in the edge outline of the picture.

In a normal scene, the portion of the picture described by edges is relatively small with respect to the picture area. Standard television must make provision for the occurrence of a high-frequency edge at any point in the picture. It is this requirement that necessitates the large bandwidth for commercial television transmission. However, by transmitting only the edges of the picture uniformly redistributed in time, a significant bandwidth reduction can be realized over conventional television transmission.

Bandwidth reduction obtained by this means depends upon the removal of the spatial redundancy within a picture. A further degree of bandwidth reduction is possible by removing the temporal redundancy between time separated picture frames by performing edge detection on an artificial video signal obtained from an element-by-element subtraction of frames.

The ability to remove redundancy spatially within a frame, and temporally between frames is transformed into a bandwidth reduction by uniformly redistributing the non-redundant picture information over the transmission time period that would be required for conventional transmission. Alternately, a transmission time reduction may be obtained by transmitting the non-redundant information at the same rate as with a conventional system. This tradeoff is always possible. In the subsequent discussion the term bandwidth reduction may be validly replaced by transmission time reduction by the appropriate alteration of the transmission rate.

With the stop-scan system of video signal gathering utilized in conjunction with edge detection, the time redistribution of edges can be performed without the need for a large capacity buffer memory at either the transmitter or receiver of a communication system. The stop-scan principle is simply to search for an edge by scanning a picture at a higher than normal rate; when an edge is detected, the scanning is stopped until the edge is coded and transmitted, at which time scanning is resumed.

The possibility of removal of spatial redundancy between picture elements within a frame as well as temporal redundancy removal between frames by stop-scan edge detection has led to the investigation of the following bandwidth reduction systems[1]:

(1) Basic Stop-Scan Edge Detection System;

(2) Line Correlation Stop-Scan Edge Detection System;

(3) Vector Correlation Stop-Scan Edge Detection System;

(4) Frame Difference Stop-Scan Edge Detection System.

The following sections present a capsule summary of the operation of these systems.

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[1] Although edge detection may be used in analog carrier modulation communication systems, as shown in appendix II, the greatest returns in bandwidth reduction are realized for digital communication systems. Accordingly, the edge detection systems described herein have been developed for digital communication links.

2.2 Basic Stop-Scan Edge Detection System

In the basic stop-scan edge detection system, as a camera scans the image of a scene, the difference in brightness between adjacent picture elements is obtained. If the brightness difference exceeds a threshold value an edge is said to exist[1]. For bilevel pictures the position of edges is sufficient to completely characterize a picture. The amplitude of the video signal at an edge plus the position of the edges describes fully a multilevel picture. Separate versions of the basic system are given below for the processing of bilevel and multilevel pictures.

2.2.1 Bilevel System

Figure 2-1 illustrates the block diagram of a typical transmitting and receiving encoding unit for a bilevel stop-scan edge detection system. On external command, the vidicon camera provides a pulse whose amplitude is proportional to the brightness of a picture element at which the camera beam is pointing. The position of the beam is controlled by a "stair step" type horizontal and vertical scan signal generated by the camera control unit. Figure 2-2 depicts the horizontal scan voltage, which is proportional to the hori-

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[1] Appendix III contains a discussion of techniques of forming edges.

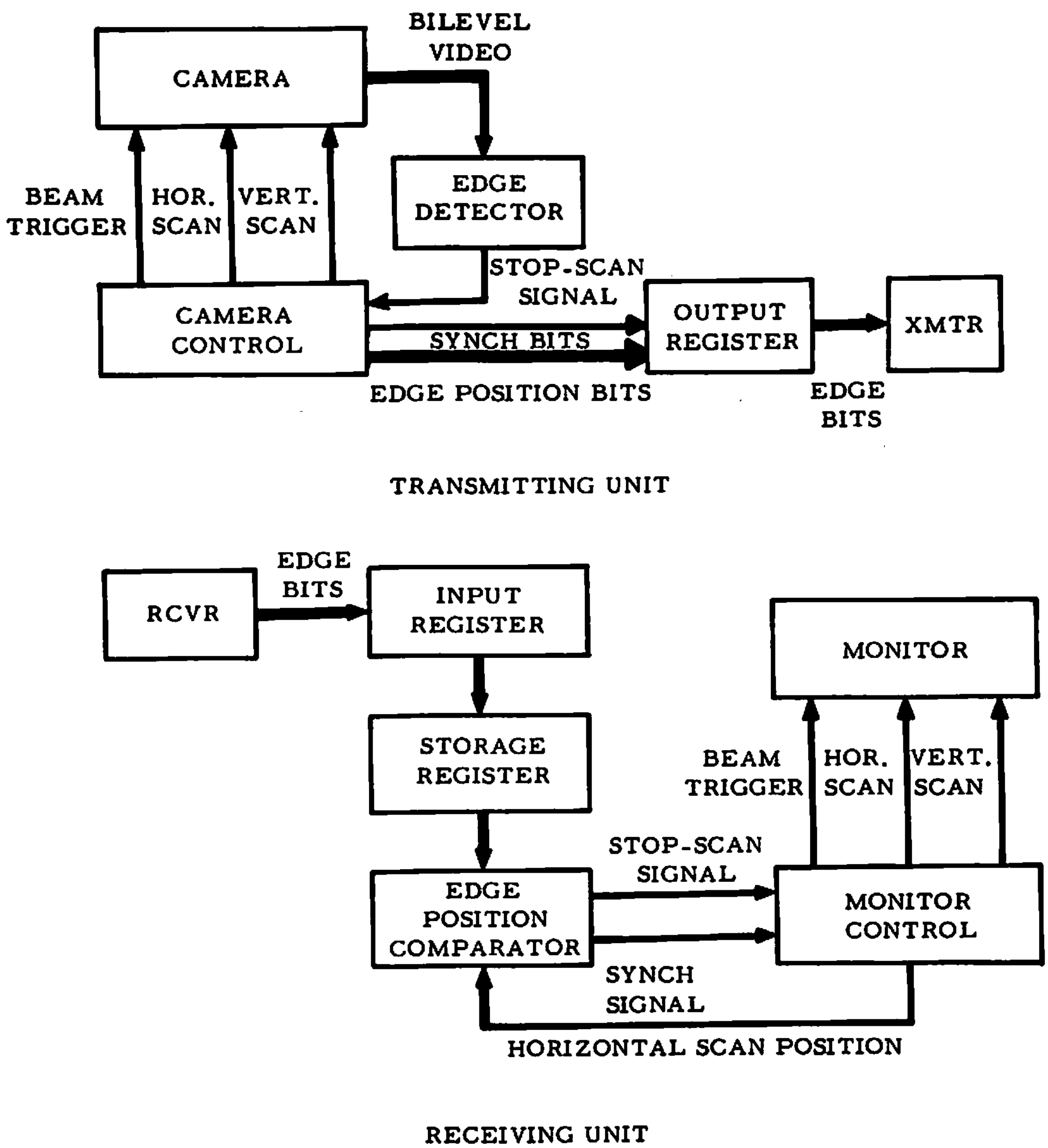


Figure 2-1. --Basic bilevel stop-scan edge detection system

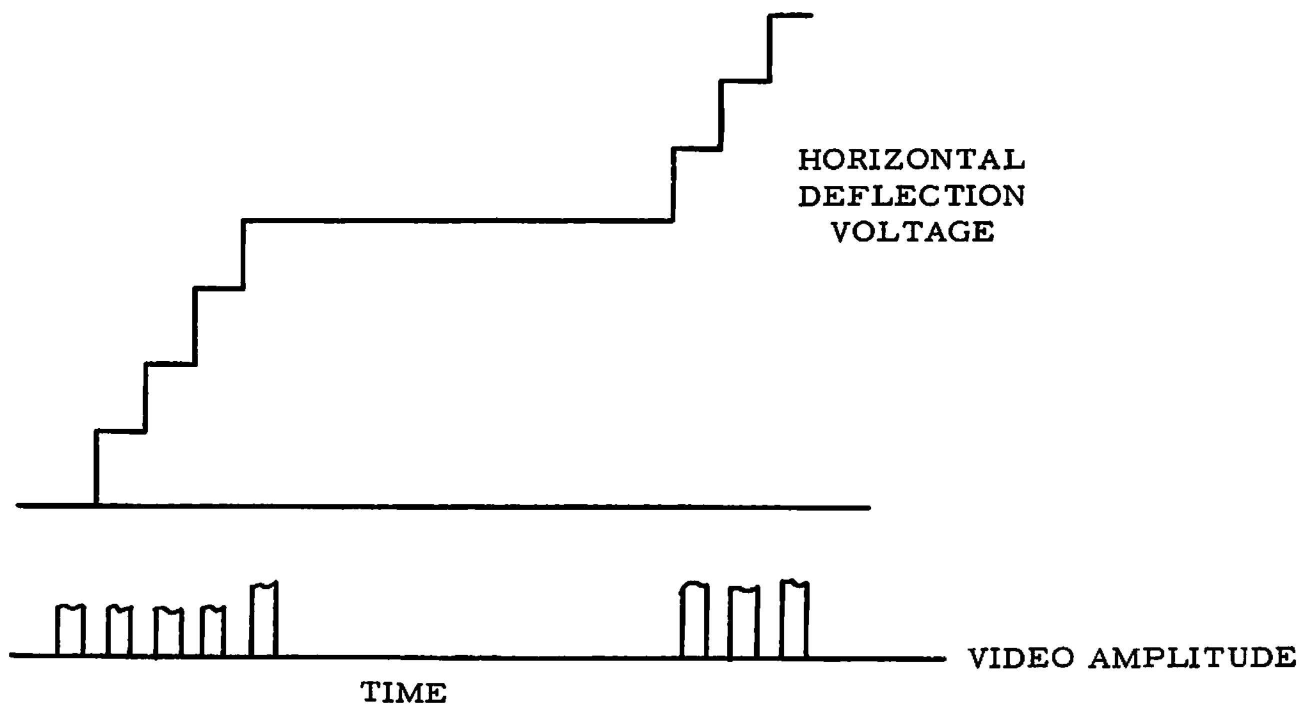


Figure 2-2. --Example of horizontal scanning and video output

zontal deflection distance along a picture line, and the pulse output of the camera. Whenever the horizontal scan advances one step, the camera is triggered to produce a video output pulse. The scan beam position is periodically halted in the stop-scan picture information gathering process.

Each video pulse generated by the camera is compared in amplitude to its predecessor by the edge detector. If the difference in amplitude exceeds a threshold value an edge exists, and a stop-scan signal is generated to halt the scan. When the previous edge encountered has been transmitted, the position of the present edge given by a set of edge position bits is transferred in parallel to the output register, and then shifted serially to the transmitter. Camera scanning then resumes to complete the edge processing cycle. The edge position for a given edge is measured as the number of picture elements scanned since the previous edge occurred as specified by an element counter in the camera control unit.

In the transmitting unit the scanning rate is synchronized with the edge transmission rate so that a maximum specified number of elements is scanned between the transmission of edges. This number is called the maximum run length. If no natural edge is detected in the picture after a maximum run length of elements is scanned, a timing signal called a pseudo edge is transmitted as a unique set of edge code bits. By this procedure the edge code words can be kept to a fixed length tailored to the informational content of the picture. At the end of each line a synchronization signal is transmitted as another unique set of edge code bits.

The edge coding process is illustrated by the example of figure 2-3 which assumes a maximum run length of 14 elements. A natural edge is encountered at the element positions marked by an "E"; at the position marked by a "P" a pseudo edge is generated; and at the end of the line marked by an "S" a synch signal is transmitted. An edge position may thus be described by 14 states of 4 flip-flops with two states alloted for a pseudo edge and synch signal. The following code could be utilized.

pseudo edge	0 0 0 0
run length 1	0 0 0 1
" " 2	0 0 1 0
.	.
.	.
.	.
run length 14	1 1 1 0
synch	1 1 1 1

In the receiving unit of figure 2-1 the received edge code bits are transferred serially to the input register. When the input

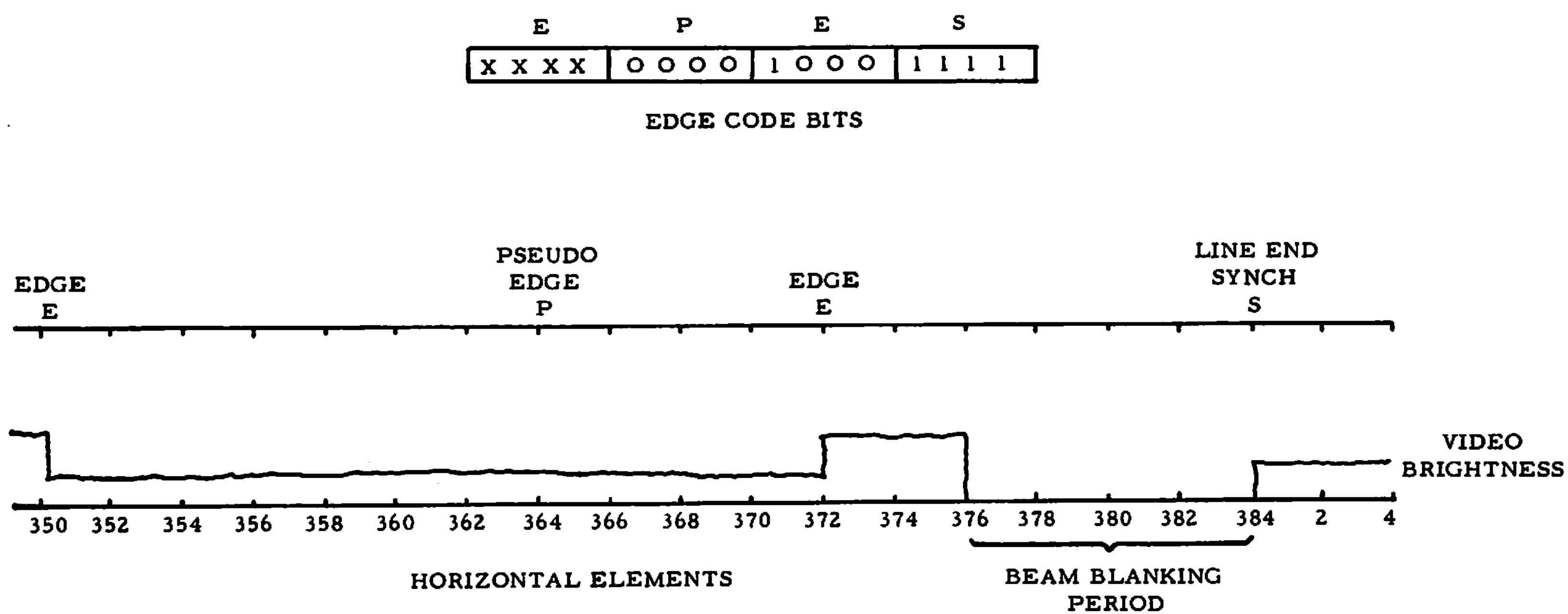


Figure 2-3. --Example of bilevel edge coding

register is filled, its contents are shifted in parallel to the storage register, and the next set of edge code bits is accepted into the input register. Upon the filling of the storage register, the horizontal scan system in the monitor control unit, which is synchronized to its counterpart in the camera control unit, begins scanning the monitor. An element counter simultaneously initiates counting. When the state of the element counter equals the contents of the storage register, a stop-scan signal is generated by the edge position comparator to halt the scan, reset the element counter, and to generate the display of the edge in the storage register. The next set of edge code bits in the input register is then transferred to the storage register for the processing of the next edge.

2.2.2 Multilevel System

The operational concept of a stop-scan edge detection system for the processing of multilevel pictures is the same as a bilevel system with the exception that the amplitude of the video signal at each edge must be coded and transmitted along with the edge position. The receiver decodes the video amplitude at each edge and reconstructs the video signal. For most applications, 6 to 8 video amplitude levels are adequate with proper amplitude quantization.

Figure 2-4 illustrates block diagrams of the transmitting and receiving units of a typical multilevel system. At the transmitter,

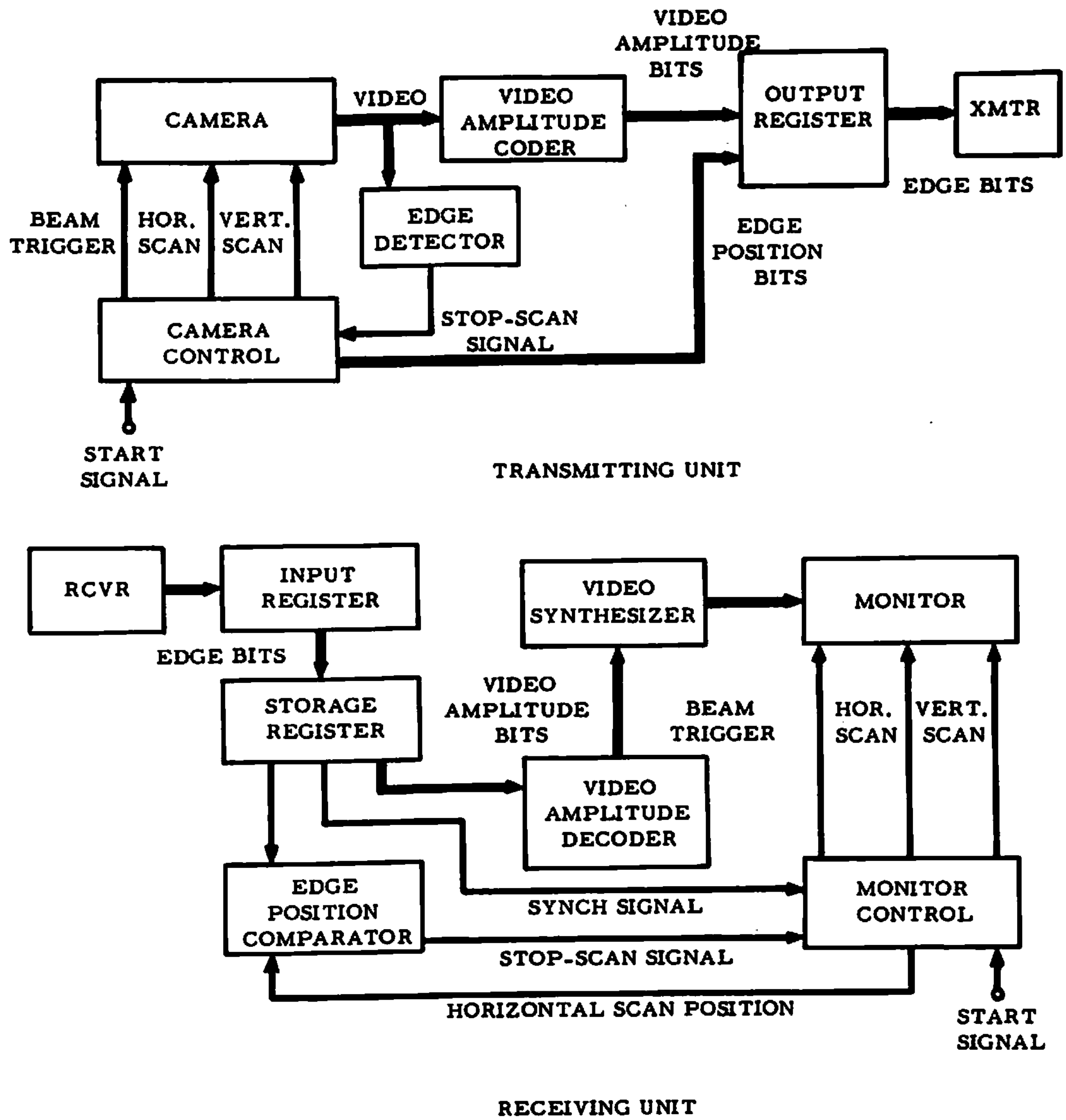


Figure 2-4.--Basic multilevel stop-scan edge detection system

whenever an edge occurs, the amplitude of the last video pulse processed is quantized and coded by the video amplitude coder. The edge amplitude code bits are then transferred in parallel to the output register along with the edge position bits.

In the receiver, the edge code bits are transferred serially to the input register and then shifted in parallel to the storage register. When an edge comparison is made, the amplitude bits in the storage register are decoded by the video amplitude decoder. The decoder controls the amplitude of the reconstructed video signal which is generated by the multilevel video synthesizer.

2.3 Line Correlation Stop-Scan Edge Detection System

The redundancy between elements of adjacent lines is essentially the same as the redundancy between adjacent elements. Thus, some type of element-to-element bandwidth reduction could be applied to vertical strings of elements. To accomplish vertical edge detection, however, would require the storage of a complete frame of a picture, whereas, horizontal stop-scan edge detection requires virtually no storage of picture information. For this reason, edge detection is applied only to horizontal strings of elements. However, when using edge detection along a horizontal line of elements, it is possible to achieve a further reduction in bandwidth by removing the redundancy of identical edges between adjacent horizontal lines.

The philosophy of this edge line correlation method of bandwidth reduction is to examine adjacent lines and to transmit only one edge of a vertical pair of edges of the same amplitude. As an example, in figure 2-5, identical edges, (2) and (5), appear in the same line positions in the first and second lines. It is not necessary to transmit edge (5) if, when edge (2) is transmitted, an added bit of information is sent to indicate that another edge of the same amplitude should be inserted below edge (2). Thus, in this example, edges (1), (2), (3), (4), and (6) are transmitted in that order. Edge (2) is coded to indicate a vertical edge correlation. At the receiver, an edge identical to edge (2) in amplitude is placed in the position that edge (5) occupied in the original picture. The result of this operation is that fewer edges are required to describe a picture and, therefore, the transmission bandwidth is proportionately reduced.

Figure 2-6 illustrates a block diagram of a line correlation edge detection system. The transmitting unit is nearly identical to the basic edge detection system except for the inclusion of an edge line memory consisting of a shift register for each video amplitude bit. The length of the register is equal to the number of active

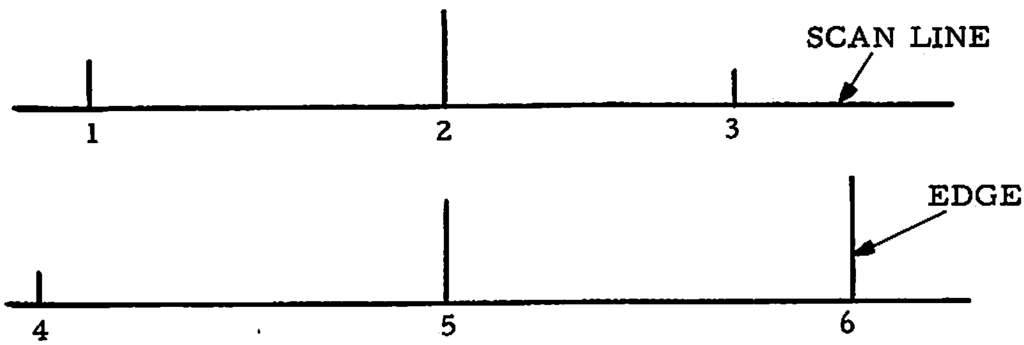


Figure 2-5. --Example of line correlation of edges

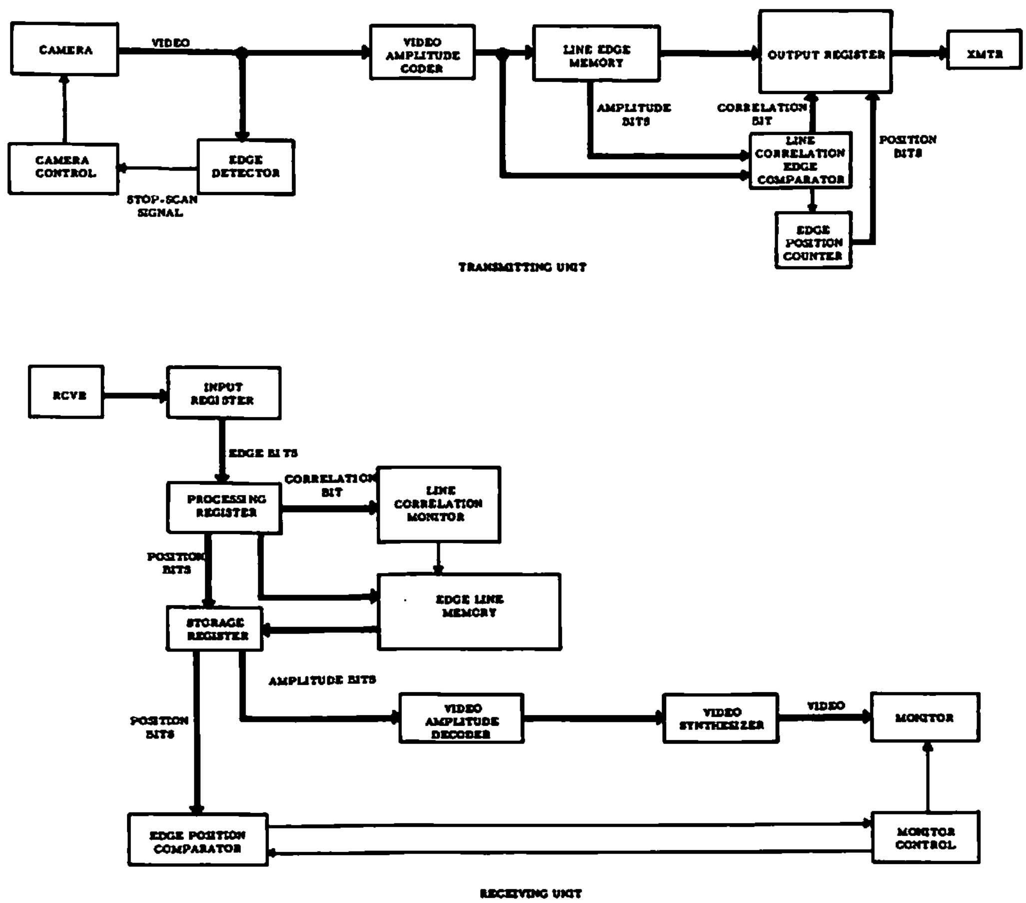


Figure 2-6. --Line correlation stop-scan edge detection system

elements in a line. For line correlation edge coding, for example, each edge may be coded by three video amplitude bits, five position bits, and one bit for correlation. The correlation bit is an extra bit of information to indicate whether a correlation has been made between adjacent vertical edges. In order to make a correlation comparison test, the amplitudes of edges of a complete line of the picture are stored in the line edge memory. The position within the memory indicates the edge position. As each edge is generated, it is placed in the memory if no correlation is present between the new edge and the adjacent edge from the line above. If the two edges are equal, the most recent edge encountered is discarded, and the correlation bit of the upper edge is set to indicate a line correlation.

The receiving unit contains a processing register, a line edge memory, and a correlation monitor. The line correlation monitor examines edge words stored in the processing register, and transfers an edge word to the line edge memory if the correlation bit indicates a line correlation. If no line correlation is indicated, the edge is decoded immediately. Each edge word in the line edge memory is transferred back to the processing register at the same element position of the next line for decoding.

2.4 Edge Vector Stop-Scan Edge Detection System

Edges in a picture often fall along fictitious vectors about a terminal edge as shown in figure 2-7. In such cases it is only necessary to transmit the position of the terminal edge, the length of the edge vector, and its slope. For example, in figure 2-7 there exist three edge vectors indicated by dotted lines. The terminal edges are circled, and the slope and length of each edge vector is denoted.

This type of edge processing removes a considerable amount of redundancy, and enables a large bandwidth reduction. The price paid, however, is the requirement of storage of a number of lines of the picture, and the implementation of a decision circuit to recognize edge vectors and determine their length and slope.

The block diagram of figure 2-8 shows a vector correlation edge detection system which is capable of coding edge vectors of up to two units in length with slopes of +1, -1, and infinity. The system is similar to the line correlation system except that three lines of edges must be stored, and the edge vector detector must examine an array of elements to determine if an edge vector exists. For this system, each edge vector is coded by six edge position bits, three video amplitude bits, two vector slope bits, and one vector length bit. Only the amplitude bits are stored in the vector edge memory. During operation, the vector detector examines the edges of the

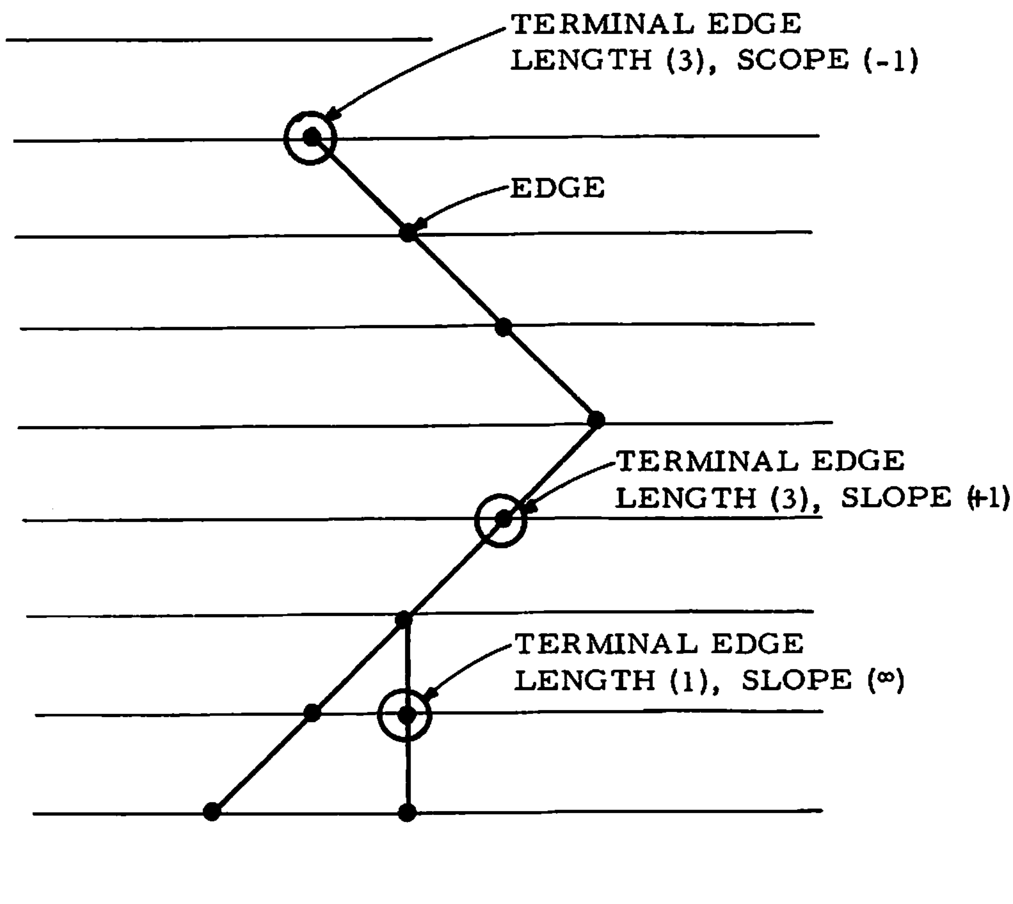


Figure 2-7. --Example of edge vectors

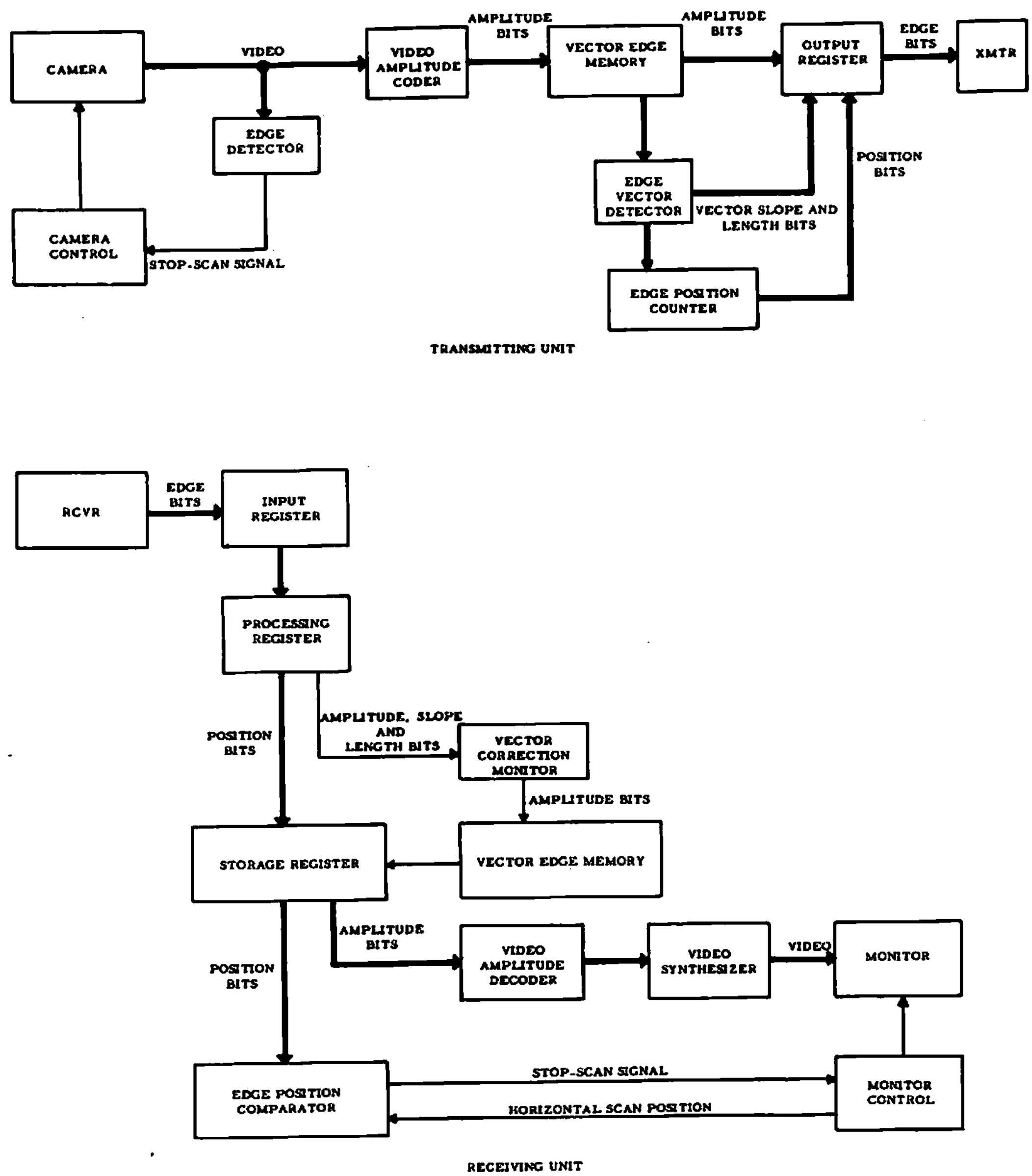


Figure 2-8. --Vector correlation stop-scan edge detection system

three lines of the memory with a vector pattern recognition circuit. If an edge vector is detected, its slope and length about the terminal edge are coded and transferred to the output register. The edges comprising the vector are simultaneously discarded from the memory.

In the receiving unit a vector correlation monitor examines each edge vector word in the processing register, and reconstructs the edge composing the vector for storage in the vector edge memory. These restored edges are inserted into the edge decoding system at the appropriate points during scanning.

2.5 Frame Difference Stop-Scan Edge Detection System

A large potential television bandwidth reduction is possible by eliminating the redundancy between adjacent frames of real time and slow scan television systems. In most scenes transmitted there is relatively little change in detail between adjacent frames. Thus, by only transmitting the suitably coded change in detail referenced to an initially transmitted frame, a significant bandwidth reduction may be realized.

One very promising method of redundancy removal between frames is to form the difference of the brightness of spatially adjacent elements in time adjacent frames as shown in figure 2-9. The frame difference signal is reduced in redundancy by a large factor,

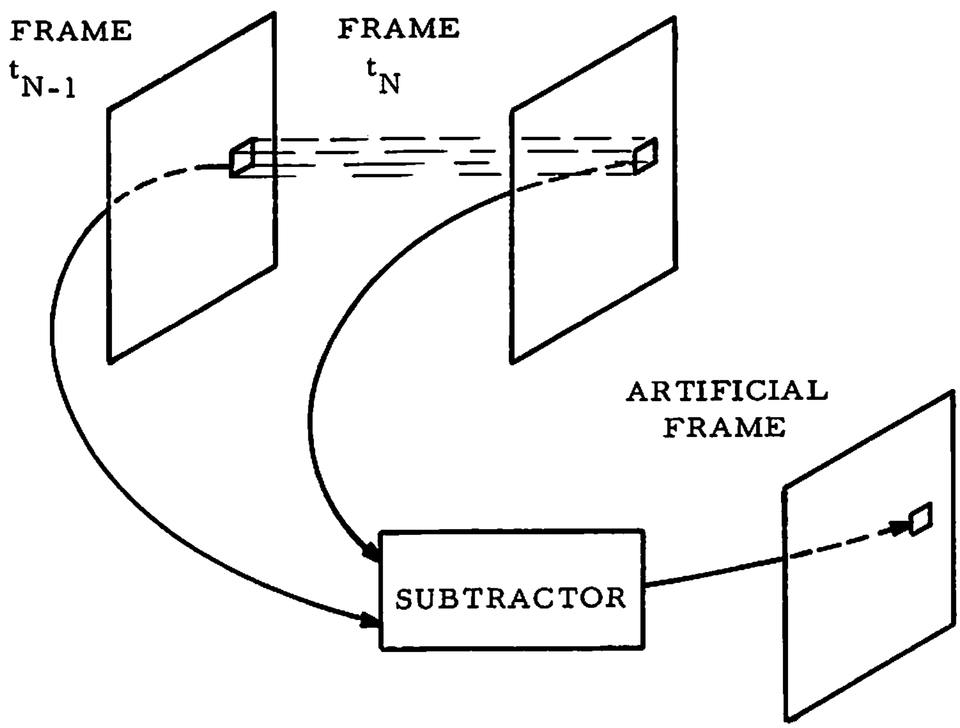


Figure 2-9. --Frame difference concept

but its bandwidth is still large since the frame difference signal may have variations in the brightness of two spatially adjacent elements. A bandwidth reduction may be realized by time redistributing the frame difference signal information over a frame period. This may be accomplished efficiently by applying stop-scan edge detection coding to the frame difference signal as if it were a serially generated video signal from a single frame. Thus, not only may the frame differences be redistributed in time by the stop-scan process, but also a further bandwidth reduction may be obtained by considering the frame differences as edges of an artificially derived frame. The reference frame which is periodically transmitted can also be processed by stop-scan edge detection. Following this procedure, a compound bandwidth reduction by spatial and temporal redundancy removal is obtained.

A functional block diagram of a frame difference stop-scan edge detection system is shown in figure 2-10. In the transmitting unit, the camera begins generating a sequence of frames at a high frame rate. The first frame of the sequence is stored in two storage tubes after passing through a video gate. The video gate is controlled by a frame timing counter in the camera control unit. While the remaining frames of the sequence are being generated, the first picture stored in the upper storage tube is coded by an edge detection

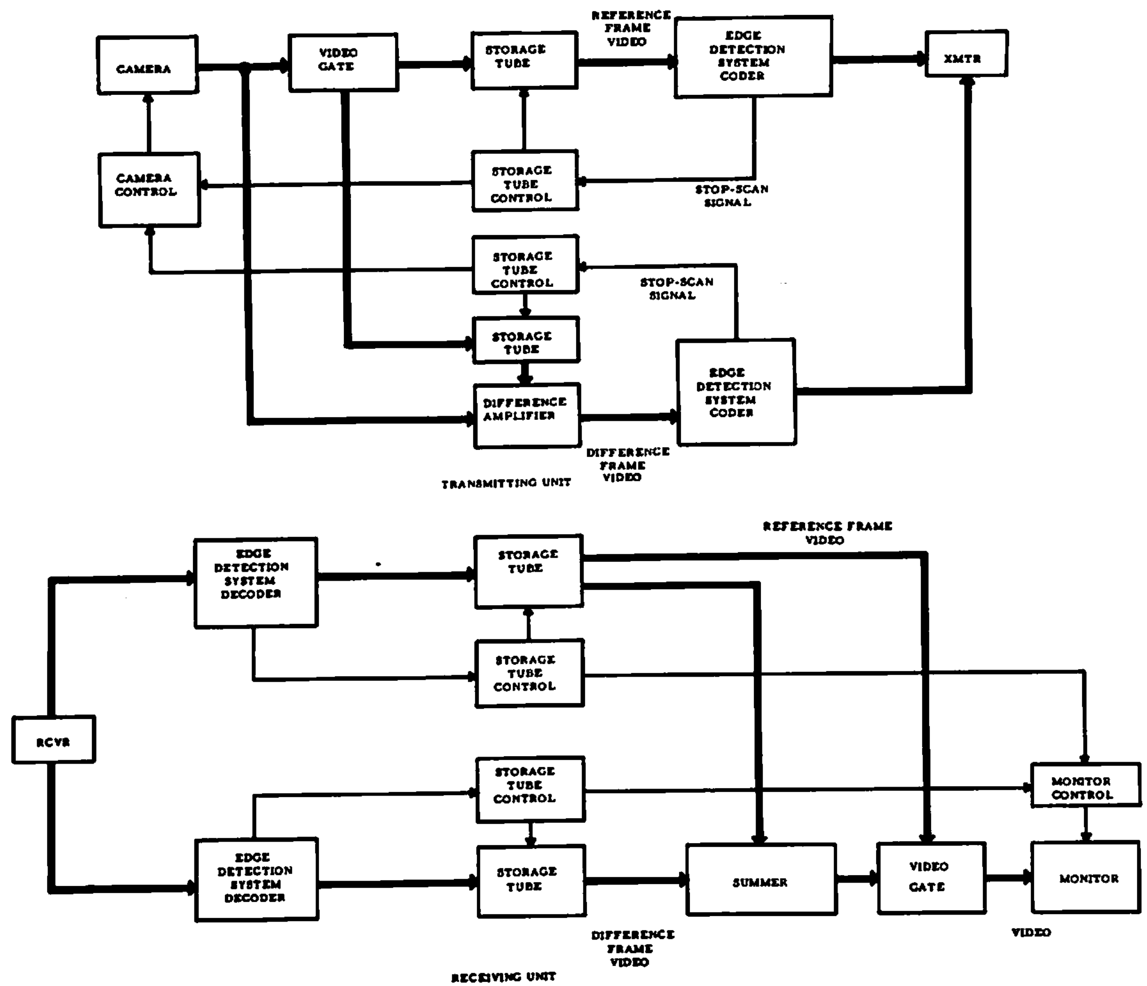


Figure 2-10.--Frame difference stop-scan edge detection system

system coder, and then transmitted over the frame sequence period. At the same time, the subsequent frames of the camera are subtracted element by element from the first frame picture which is readout from the lower storage tube. The difference signal is regarded as an ordinary video signal, and edge coded. The edge coder of the reference frame channel operates in a similar fashion to the basic edge detection system coder except that the scan of the storage tube is operated in a stop-scan mode, rather than the camera itself. The storage tube, in essence, becomes a new video signal source. The difference channel edge coder controls the scan of both the storage tube and the camera during the stop-scan edge coding process.

At the receiver, the edge coded reference frame signal is decoded by an edge detection system decoder controlling the scan of the upper storage tube. The reconstructed reference frame is then displayed on the monitor as the first frame of a display sequence. In the meantime, each edge coded frame difference signal is decoded by an edge detection system decoder controlling the scan of the lower storage tube. The reconstructed difference signal is then added to the frame reference signal to yield a reconstructed video signal.

CHAPTER 3

PSYCHOPHYSICAL VIEWING PROPERTIES

The psychophysical properties of vision play a significant role in the development of television systems. They not only dictate the operational requirements of television systems, but also form the basis for television bandwidth compression techniques. Table 3-1 contains a list of the most important psychophysical properties of vision as they relate to the operational parameters of television systems.

TABLE 3-1

RELATIONSHIP BETWEEN PSYCHOPHYSICAL PROPERTIES OF VISION AND OPERATIONAL PARAMETERS OF TELEVISION SYSTEMS

Psychophysical Properties	Operational Parameters
Contrast fidelity	Contrast resolution
Acuity angle Visibility of details of moving objects Temporal adaption to spatial detail	Spatial resolution
Illusion of motion Perception of flicker	Frame rate

3.1 Spatial Resolution

The minimum acuity angle of the eye specifies the smallest angle for which the eye can perceive a spatial gradient in intensity. Minimum acuity angles of fractions of a minute of arc have been measured under laboratory conditions. For television systems at a viewing distance of 4 to 5 times picture height, 2 minutes of arc has been generally accepted [176] as an adequate angle subtended by a single picture element.

Due to the discrete nature of line scanning there is some probability that optical detail will fall between television lines, and be missed during scanning. This probability called the Kell factor has been empirically found to be about 0.71 [82].

The sacrifice of spatial resolution in independent picture transmission systems in order to reduce bandwidth is generally unacceptable. In real time, and to some degree in slow scan systems, spatial resolution can be reduced under certain conditions without severe picture degradation. The first of these conditions relates to the fact that the eye cannot distinguish the detail of moving objects very well. Indeed, the blurriness of a moving object is often more natural to a viewer than a finely detailed object. Law [54] has suggested a television bandwidth reduction system based upon this phenomenon.

The second condition for which the eye will accept reduced spatial resolution occurs when a camera shifts to a different scene. Seyler and Budrikis [98] found that for scene changes in film, about one second was required for an observer to regain his spatial resolution to the new scene. An investigation into television bandwidth reduction systems based upon the exchange of spatial resolution for bandwidth in the case of changing scenes has been conducted by Seyler [147].

3.2 Contrast Resolution

In digital television systems the contrast resolution specification determines the number and placement of video amplitude quantization levels. Goodall [43] has determined that 32 levels of uniform video element quantization give an adequate contrast resolution. For fewer than 32 levels of quantization the annoying effect of gray scale contouring becomes noticeable. Gray scale contours are patches of elements which are displayed at a gray scale level one step higher or lower than the surrounding elements even though the brightness of the entire area is nearly constant, or at least spatially changes in brightness slowly. The contours occur when the video amplitude lies near a quantization level. Slight changes in the video amplitude, or camera noise cause a much larger step difference in brightness. If the quantization scale contains many levels the steps will be small, and the gray scale contouring will not be noticeable.

Kretzmer [21] and Schreiber [47] observed that gray scale contouring only effects regions of relatively slowly varying brightness. This observation led to the proposal of television bandwidth reduction systems in which the video signal is split into frequency bands with the quantization scale inversely proportional to the video frequency. In systems with two bands, the low frequency band of 10% of the bandwidth is quantized into 8 levels, while the high frequency band is quantized into 32 levels.

Another approach to reducing the required contrast resolution using a tapered quantizer scale has been investigated in studies of Deltamodulation television bandwidth reduction systems [69]. In these systems, the quantizer scale is tapered to make the quantization error proportional to the video amplitude. With a tapered scale, 6 - 8 levels of quantization provide acceptable pictures.

In a third technique developed by Roberts [24] pseudo-random noise is added to the video signal before quantization. The same pseudo-random noise is subtracted from the video signal in the decoding process. The result of this processing is to randomize the video amplitude levels from element to element and minimize the visual effects of gray scale contouring. Eight levels of quantization suffice for contrast resolution with this type of pseudo-random coding.

3.3 Frame Rate

The frame rate of a television system determines the amount of flicker and image motion fidelity in displayed pictures. Flicker is the low frequency brightness change caused by sequentially displaying frames. Haantjes and de Vrijer [135] have determined critical frame frequencies for which flicker is acceptable. They have shown that this critical frequency increases with brightness, retinal area involved, and ratio of dark to light time. A full frame rate of 20 to 30 frames per second has been found acceptable. The technique used in commercial television to reduce flicker with a fixed frame rate, is to scan every other line of a frame, and to transmit this field of elements at the original frame rate. Two fields of video per frame are displayed with a corresponding halving of the flicker rate. Unfortunately, extensions to line interleaving cannot be easily carried further because of patterning and dot crawling effects in the displayed picture, in addition to the degradation of image motion fidelity. In space and relay type television systems, frame conversion techniques are utilized to minimize flicker. Each received frame is stored and displayed a number of times to satisfy the critical frame rate flicker requirements.

Assuming that flicker is made acceptable by frame conversion, the lower limit of frame rate is determined by the ability of the system to capture the illusion of motion. For low frame rate continuously scanned systems, objects in a scene may move appreciably during a single frame. In such cases, the image of the object will be blurred and misshapen. A certain amount of blur is acceptable for moving objects in television systems. The usual criterion is that the blur should not be any greater than would be the blur of objects passing the optical path of a viewer under the same conditions of visual acuity angle. Blurring of moving objects in a low frame rate system can be minimized by shuttering the camera to capture the image in a short period of time, and then scanning the image over the frame period. While blurring is minimized, the effect of image jump is enhanced; moving objects appear to move in steps against a background rather than continuously.

Several techniques of bandwidth reduction based upon multiple line and dot interlace of the scan beam have been developed [57, 111]. The principle of these systems is to spatially sample a fraction of the elements of a complete frame during each field scanning period. The samples are spatially interlaced so that after several fields have been scanned every element of a frame will have been scanned.

By transmitting each field at a reduced rate, a bandwidth reduction may be realized without image jump. However, an artificial blur or image breakup occurs when an object moves appreciably during the scanning of fields. Only a portion of the displayed elements describe the actual position of the object. The remainder of the elements indicate the time sequence of the previous positions of the object.

CHAPTER 4

INFORMATION THEORETIC ANALYSIS

An information theoretic analysis has been performed for edge detection coding to set bounds on the potential bandwidth compression, and to provide an indication of possible areas in which extensions or improvements to the coding method may be profitable.

4.1 Edge Position Coding Model

The first order Markov process model is an effective vehicle for the analysis of edge position coding since, by definition, an edge exists only when an element being scanned differs significantly from the previous adjacent element scanned. The reasonableness of this definition is supported by the experimental results of Shrieber [8]. In these tests the entropy for a 64 level picture for a single element Y_i was found to be $H(Y_i) = 4.39$ bits. The entropy considering knowledge of the previous element was $H(Y_i | Y_{i-1}) = 1.91$, and considering two previous elements was $H(Y_i | Y_{i-1}, Y_{i-2}) = 1.49$. Thus, while Y_{i-1} provided an average of 2.48 bits of information about Y_i, element Y_{i-2} provided only an additional 0.42 bit.

For the first order Markov process model of edge coding, the probability of occurrence of edges is assumed to be independent. This assumption is completely applicable for the basic edge detection system and for the frame difference system. In the case of the coding of edge vectors and edges correlated between lines, the probability of occurrence of an edge is modified to include only the upper edge of a line correlated pair of edges, or the terminal edge of an edge vector. In this manner, the forming of edge line correlations and edge vectors effectively reduces the spatial density of edges, and is reflected in a lower value of the probability of occurrence of an edge. Thus, for the edge coding model let:

p = probability that a natural (non-pseudo) edge occurs at the i^{th} element

$q = 1 - p$ = probability that no edge occurs at the i^{th} element.

In order to establish the theoretical bound of bandwidth compression for edge position coding, it will be necessary to derive the probability distribution of edge runs. The actual coding technique employed in the edge detection coding systems limits the edge runs to a maximum edge run length of M elements. When M elements have been scanned without encountering a natural edge, a video sample and associated element position (pseudo edge) is transmitted, and the search for the next natural edge is resumed. The reason for this procedure is to provide a code with relatively short edge run code words to minimize the effects of edge position errors. Before considering the probability distribution of edge runs including pseudo edges, it will be instructive to discuss the unrestricted distribution of natural edge runs in order to assess the cost of pseudo edge run coding.

4.2 Entropy of Natural Edge Position Coding

Julesz [32] has experimentally verified that the probability of Z elements being scanned between natural edges is described by a geometric distribution of the form

$$P_r(Z=j) = q^{j-1}\, p \tag{4.1}$$

The associated entropy[1] per edge run is

$$H(Z) = -\sum_{j=1}^{\infty} q^{j-1}\, p \,\lg q^{j-1}\, p \tag{4.2}$$

or simplified

$$H(Z) = -\frac{q \lg q + p \lg p}{p} \tag{4.3}$$

---

[1] lg represents the logarithm to the base two.

4.3 Entropy of Pseudo Edge Position Coding

The modified edge run distribution $P_r(Z_M=j)$, which includes the occurrence of pseudo edges, is found by truncating the natural edge run distribution to a maximum range of M elements. All natural edge runs greater in length than M lead to pseudo edges at M. Thus, the modified edge run distribution is

$$P_r(Z_M=j) = q^{j-1}p + \delta(j-M)\sum_{k=M+1}^{\infty} q^{k-1}p \qquad 1 \leq j \leq M \tag{4.4}$$

where $\delta(j-M)$ is the unit impulse function. Summing the series yields

$$P_r(Z_M=j) = q^{j-1}p + q^M\delta(j-M) \qquad 1 \leq j \leq M \tag{4.5}$$

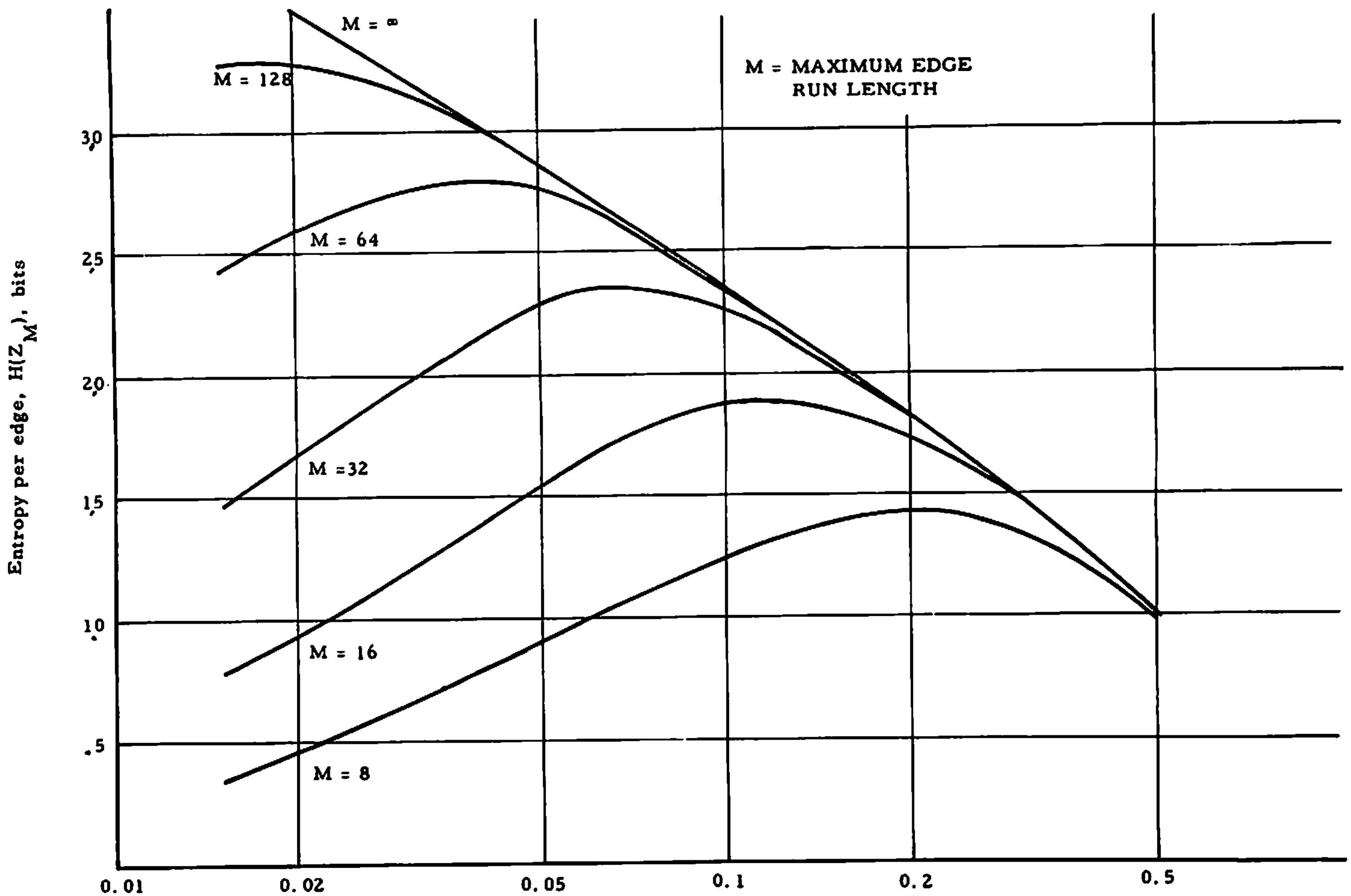
The corresponding entropy of an edge run is

$$H(Z_M) = -\sum_{j=1}^{M-1}(q^{j-1}p)\lg(q^{j-1}p) + (q^{M-1}p+q^M)\lg(q^{M-1}p+q^M) \tag{4.6}$$

In expanded form

$$H(Z_M) = -(1-q^{M-1})\frac{(p\lg p + q\lg q)}{p} \tag{4.7}$$

The entropy of an edge run is plotted in figure 4-1 as a function of M and p. The curve for M equal to infinity corresponds to the entropy for natural edge position coding.



Probability of edge occurrence, p

Figure 4-1. --Entropy of edge runs

4.4 Entropy of Video Amplitude Coding

The entropy of each coded video sample is dependent upon the quantization scale and the number of quantization levels. In section 3.2 it was stated that a tapered quantizer scale minimizes the effects of gray scale contouring for a given number of quantization levels. The basic reason for employing a tapered quantizer is that the eye in combination with the nervous system responds nonlinearly to intensity. The response of a viewer to a visual source is approximately logarithmic in form [219].

In developing the entropy for video amplitude coding it will be assumed that the response, V, of a viewer to the intensity, Y, of an element of a visual source is given by the transfer function

$$V = \log_e (Y+1) \tag{4.8}$$

If a viewer responds linearly to steps in magnitude of the variable V, the optimum quantization scale of Y is logarithmic. Thus for a given number of quantization levels the range of V should be divided evenly. The corresponding image points of the transfer function yield the optimum quantization levels. Quantization levels for seven level video amplitude quantization are given in table 4-1.

TABLE 4-1

QUANTIZATION LEVELS FOR LOGARITHMIC INTENSITY TRANSFER FUNCTION

Level	Intensity Scale
1	9%
2	19%
3	31%
4	45%
5	61%
6	79%
7	100%

Given the optimum quantization levels, the entropy for video amplitude coding may be determined from the probability distribution of the video amplitude. Seyler [176] indicates that this distribution is exponential of the form

$$p(Y) = (\log_e a)\, a^{-Y} \qquad (4.9)$$

where a = base of distribution dependent upon class of pictures.

As an example, the exponential distribution

$$p(Y) = (\log_e 2)\, 2^{-Y} \qquad (4.10)$$

approximates Schrieber's experimental data [8] for test pictures. Table 4-2 gives the probability that a video signal with this distribution lies in the quantization bands defined in table 4-1.

TABLE 4-2

PROBABILITY DISTRIBUTION OF VIDEO AMPLITUDE

Level	Probability of Occupancy
1	.248
2	.208
3	.179
4	.143
5	.105
6	.071
7	.046

The entropy for this set of probabilities is H(Y) = 2.63 bits.

4.5 Entropy of Edge Detection Coding

The entropy of edge detection coding is the combined entropy of the edge position code, the video amplitude code, and the line or vector correlation code. The latter entropy cannot be specified because information is not presently available as to the probability of occurrence of line or vector correlations.

For basic edge coding the entropy per edge averaged over the number of edges of the source is

$$H(W) = \frac{H(Z_M) + H(Y)}{\overline{Z}_M} \qquad (4.11)$$

where $\overline{Z}_M$ = average edge run length.

From the distribution of edge run lengths with pseudo-edge position coding given in equation 4.5, the average edge run length is

$$\overline{Z}_M = \sum_{j=1}^{M} j\, q^{j-1}\, p + M q^M \qquad (4.12)$$

Upon summation

$$\overline{Z}_M = \frac{1}{p}(1 - q^M) \qquad (4.13)$$

The value of $\overline{Z}_M$ is plotted in figure 4-2 as a function of M and p.

Substituting from equations 4.7 and 4.13 into equation 4.11 yields the average entropy per element of basic edge coding.

$$H(W) = \frac{p\,H(Y) - (1 - q^{M-1})(p \lg p + q \lg q)}{(1 - q^M)} \qquad (4.14)$$

The value of H(W) is plotted in figure 4-3 as a function of M and p for H(Y) = 2.63 bits as derived in the example of the previous section. As M decreases the number of pseudo edges increases, and hence, the entropy of edge coding also increases. This entropy expression gives a bound on the minimum number of bits per element required to code a visual source by basic edge coding.

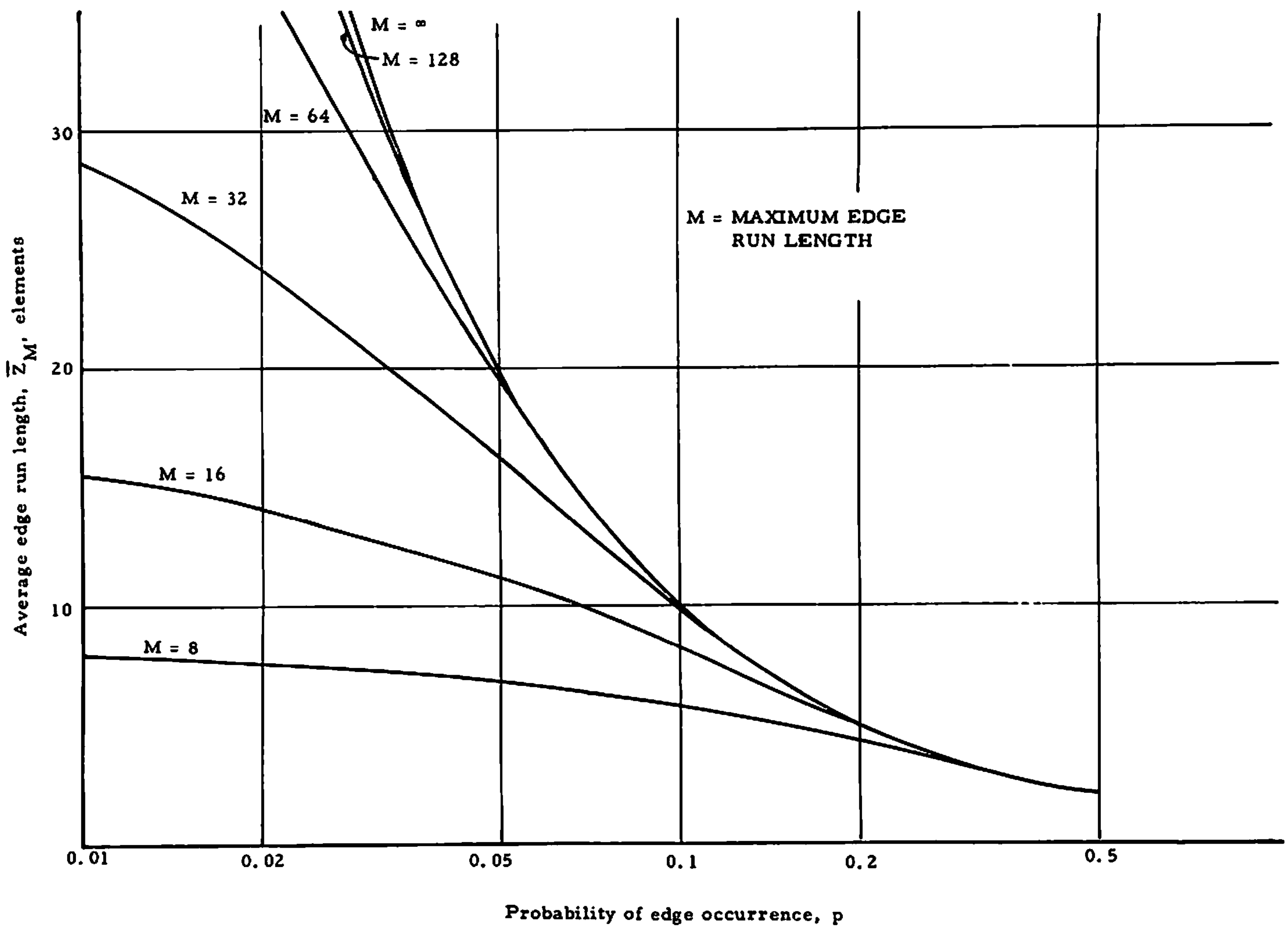


Figure 4-2. --Average edge run length

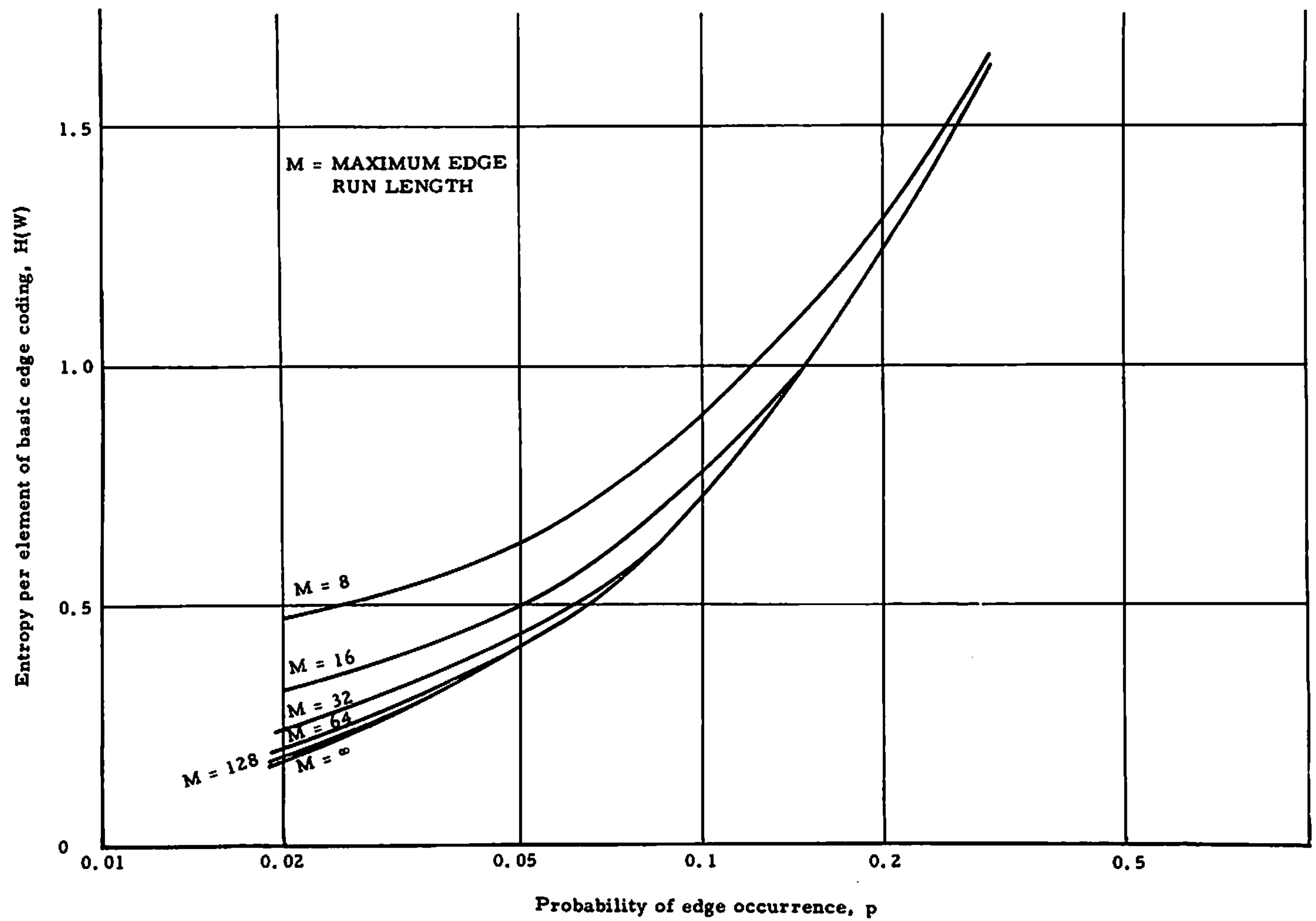


Figure 4.3.--Entropy of basic edge coding

4.6 Optimum Edge Detection Coding

The Huffman coding method [220] provides optimum edge detection codes. Table 4-3 gives the Huffman code for the video amplitude levels of the example of section 4.4

TABLE 4-3

HUFFMAN CODE FOR VIDEO AMPLITUDE CODING

Level	Code
1	11
2	10
3	011
4	010
5	001
6	0001
7	0000

The average length of each code word is 2.66 bits which is quite close to the entropy of video amplitude coding which is H(Y) = 2.63 bits.

For edge position coding the optimum Huffman code is a function of both M and p. Table 4-4 gives Huffman edge position codes and the corresponding average code word length for various values of M and p.

TABLE 4-4

HUFFMAN CODES FOR EDGE POSITION CODING

Edge Run Length	Huffman Codes			
	M = 8, p = 0.1	M = 8, p = 0.2	M = 16, p = 0.1	M = 16, p = 0.2
1	100	00	110	10
2	1111	100	0001	000
3	1110	110	0000	110
4	1101	1010	0010	0101
5	1100	1011	0100	0100
6	1011	1111	0110	0010
7	1010	1110	1110	1110
8	0	01	00111	0110
9			00110	00111
10			01011	11110
11			01010	01110
12			01111	111111
13			01110	111110
14			11111	011111
15			11110	011110
16			10	00110
Average Code Length	2.46	2.89	3.72	3.54

4.7 Constant Length Code Word Edge Detection Coding

The Huffman codes which provide optimum edge detection coding are often composed of variable length code words. In general the implementation of coders and decoders for variable length code words is much more difficult than for constant length code words. In addition, the stop-scan process is only feasible with constant length code words.

With $N_{B,E}$ bits used to code each edge separated by an average run length of $\overline{Z}_M$ elements, the average number of bits $\overline{W}$ required to code the elements of a television picture is

$$\overline{W} = \frac{N_{B,E}}{\overline{Z}_M} \tag{4.15}$$

In general each edge is composed of A amplitude bits, G position bits, and Q correlation, vector slope, and vector length bits. Thus,

$$\overline{W} = \frac{A + G + Q}{\overline{Z}_M} \tag{4.16}$$

where $M = 2^G$.

Figure 4-4 shows $\overline{W}$ plotted as a function of M and p for A = 3, and for Q = 0 bits. The heavy lines on the curves represent the minimum value of $\overline{W}$ as a function of p, and hence, determine the optimum choice of M as a function of p.

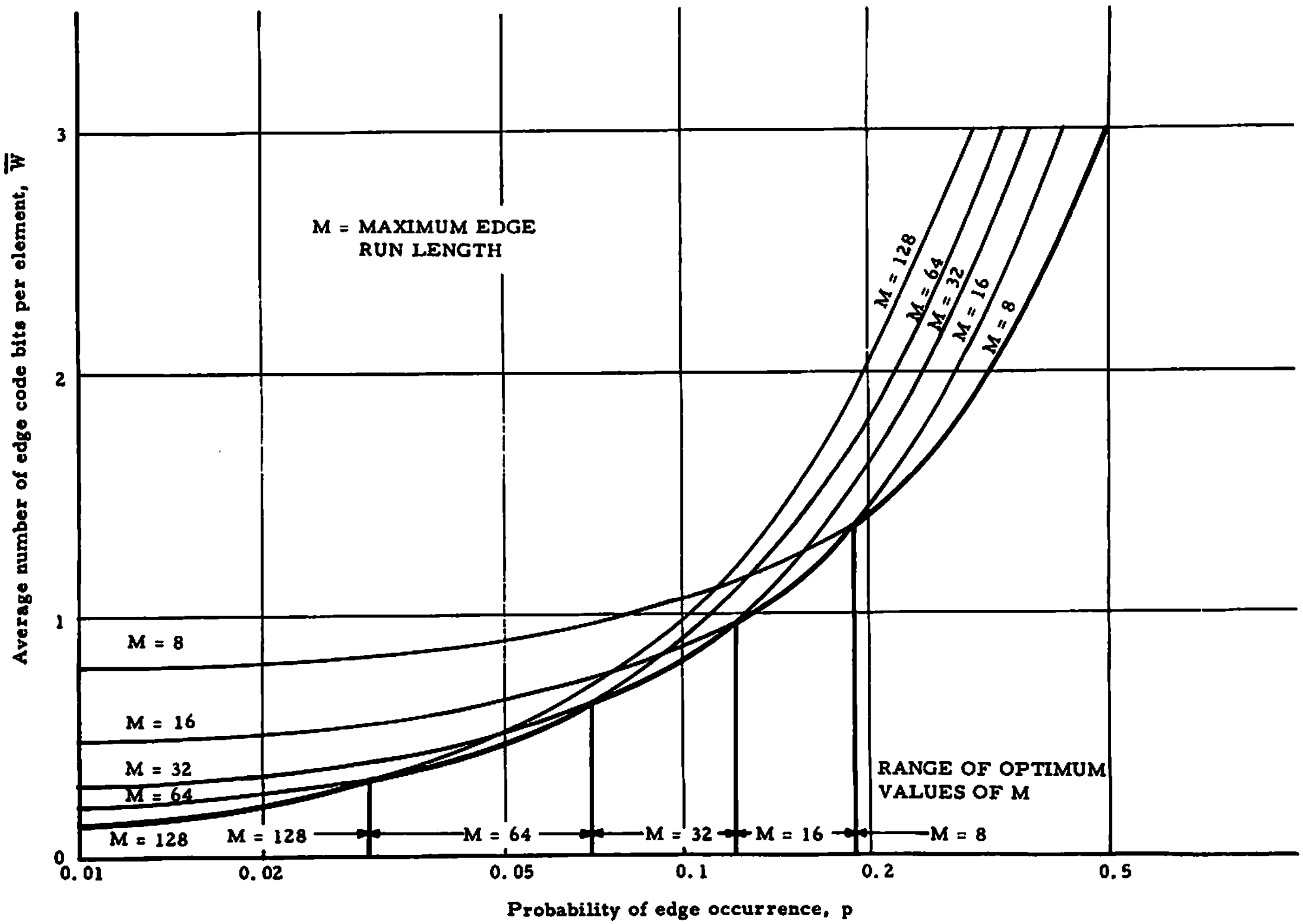


Figure 4-4. --Average number of edge code bits per element

4.8 Evaluation of Edge Coding Codes

Figure 4-5 illustrates a comparison of the constant word length and Huffman edge codes to the entropy bound of edge detection coding. The entropy bound is based upon a maximum edge run length which is restricted to 32 elements to minimize the effects of edge position errors. Similarly, the curve for the average number of edge code bits per element for constant word length coding is restricted to maximum edge run lengths no greater than 32 elements. For small values of p this restriction decreases the bandwidth reduction factor slightly. The Huffman codes are also based upon a value of M no greater than 32.

The curves indicate that the Huffman and constant word length codes come reasonably close to the entropy bound. Also, the reduction in redundancy of the Huffman code compared to the constant word length code is not sufficient to justify its use.

The bandwidth reduction potential of edge coding is the ratio of the number of PCM code bits per element (usually five), to the average number of edge code bits per element. In the range of $p = 0.1$ to 0.2, about one bit per element is required for constant word length edge coding. This results in a bandwidth reduction factor of about five.

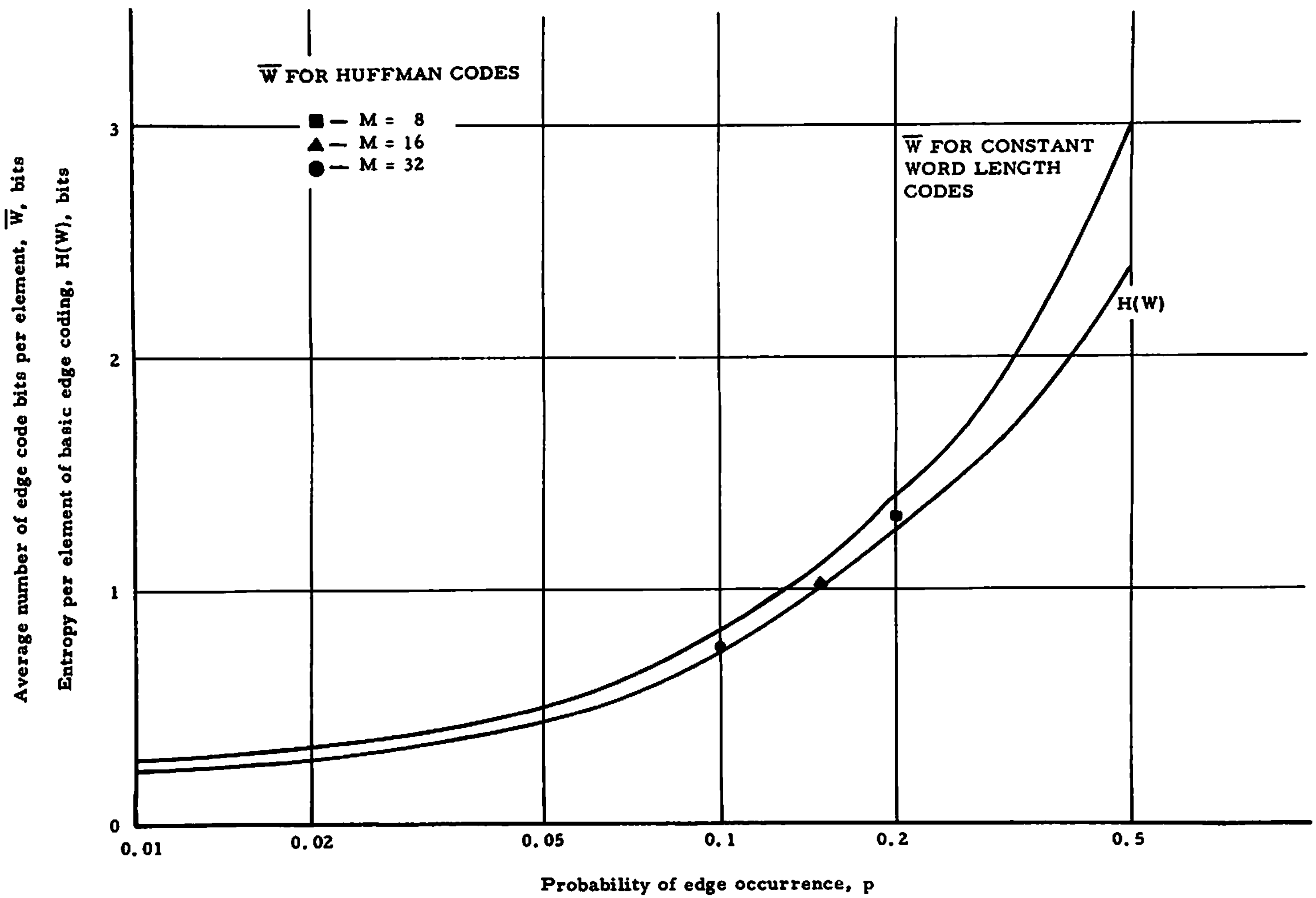


Figure 4-5.--Comparison of edge codes

CHAPTER 5

SYSTEMS ANALYSIS

5.1 Edge Transmission Rate

With stop-scan edge detection coding, three mode options are possible: (1) variable frame rate; (2) fixed frame rate; and, (3) fixed line rate. For the latter two scanning rate modes, there is an optimum edge transmission rate which is the best compromise between bandwidth compression and picture degradation.

In the variable frame rate system the time required to transmit a frame is proportional to the number of edges in the picture. A new frame is scanned only after all of the edges of a picture have been transmitted. This type of operation is only feasible for "facsimile type" systems which transmit independent pictures. Real time and slow scan systems sample time varying scenes. In order to achieve the illusion of continuous motion the time samples must be periodic, or nearly so.

For a fixed frame rate system there is some probability that a frame will not be completely scanned before the frame period is completed. In this situation a displayed picture will have a blank bar across the bottom with the resultant loss of information. The occurrence of frame underscanning can be made arbitrarily small by increasing the scanning rate and bit transmission rate, but at the price of reducing the bandwidth compression factor. One technique of eliminating frame underscanning without affecting the bandwidth reduction capability is to adaptively control the threshold for detecting edges in accordance with the amount of remaining scan time during a frame period. This practice has the disadvantage that the resolution of a reproduced picture is impaired.

In a fixed line rate system some lines may not be completely scanned. This will result in a ragged edge on one side of the picture. Line underscanning can also be eliminated by an adaptive edge threshold.

Frame and line underscanning, or edge resolution degradation due to an adaptive edge threshold, both represent picture quality impairment due to the bandwidth reduction process. However, by a conservative selection of the scanning rate for a fixed frame rate or fixed line rate system, these effects may be made negligible while still achieving a significant bandwidth reduction.

5.1.1 Variable Frame Rate System

For a variable frame rate system the average number of edges, $\overline{X}_F$, transmitted per frame is

$$\overline{X}_F = \frac{N_{D,F}}{\overline{Z}_M} \tag{5.1}$$

where $N_{D,F}$ = number of elements per frame.

5.1.2 Fixed Frame Rate System

In order to minimize the effect of frame underscanning or edge threshold degradation, it is necessary to select an edge transmission rate for which the probability of not having enough time to transmit all of the edges of a frame is very small. The number of edges in a frame, X_F, is a random variable dependent upon the detail of the picture measured by p.

The probability distribution of X_F is binomial based upon the assumption of section 4.2 that the occurrence of edges are independent. The mean and variance of the distribution are

$$\overline{X}_F = N_{D,F}\, p \tag{5.2}$$

$$\sigma^2_{X_F} = N_{D,F}\, p\, q \tag{5.3}$$

For $N_{D,F}$ large the binomial distribution may be approximated by a Gaussian distribution with the same mean and variance. Thus,

$$P(X_F) = \frac{1}{\sqrt{2\pi N_{D,F}\, p\, q}} \exp\left[-\frac{1}{2} \left\{ \frac{(X_F - N_{D,F}\, p)^2}{N_{D,F}\, p\, q} \right\} \right] \qquad (5.4)$$

Given the distribution for X_F, the probability that not more than $N_{E,F}$ edges will be detected in a frame period is set to a frame fidelity constant K_F for the maximum value of p for the class of pictures to be transmitted.

$$K_F = \int_0^{N_{E,F}} P(X_F)\, d X_F \qquad (5.5)$$

The value of the frame fidelity constant is found from subjective viewing tests to determine the allowable picture degradation due to frame overrun or edge threshold degradation.

5.1.3 Fixed Line Rate System

The procedure to minimize the effect of line underscanning or edge threshold degradation in a fixed line rate system is the same as that for a fixed frame rate system. The number of edges in a line, X_L, has a binomial distribution with mean and variance

$$\overline{X}_L = N_{D,L}\, p \qquad (5.6)$$

$$\sigma^2_{X_L} = N_{D,L}\, p\, q \qquad (5.7)$$

where $N_{D,L}$ = number of elements per line.

Approximating the binomial distribution by a Gaussian distribution yields

$$P(X_L) = \frac{1}{\sqrt{2\pi N_{D,L}\, p\, q}} \exp\left[-\frac{1}{2}\left\{ \frac{(X_L - N_{D,L}\, p)^2}{N_{D,L}\, p\, q} \right\}\right] \qquad (5.8)$$

The probability that not more than $N_{E,L}$ edges will be detected in a frame period is set to a line fidelity constant.

$$K_L = \int_0^{N_{E,L}} P(X_L)\, dX_L \qquad (5.9)$$

The value of the line fidelity constant is determined from subjective tests.

5.2 Scanning Rate

The element scan rate of the stop-scan edge detection system is dependent upon the scanning rate mode and the corresponding number of edges to be transmitted per second, frame, or line. After each edge is transmitted, the camera must examine at most the maximum run length, M, of elements.

5.2.1 Variable Frame Rate System

The number of edges transmitted per second, $N_{E,S}$, is the ratio of the transmission bit rate, R_B, to the number of code bits per edge, $N_{B,E}$.

$$N_{E,S} = \frac{R_B}{N_{B,E}}$$

with

$$N_{B,E} = A + G + Q \qquad (5.10)$$

where A = number of video amplitude bits per edge

G = number of edge position bits per edge

Q = number of correlation, edge slope, and edge vector bits per edge.

Since at most the maximum run length, M, of elements must be scanned between edges the scan rate, R_S, in elements per second is

$$R_S \geq \frac{M R_B}{N_{B,E}} \qquad (5.11)$$

5.2.2 Fixed Frame Rate System

The scan rate for a frame period, T_F, is

$$R_S \geq \frac{M N_{E,F}}{T_F} \tag{5.12}$$

where $N_{E,F}$ = number of edges transmitted per frame.

The corresponding transmission rate is

$$R_B = \frac{N_{B,E} N_{E,F}}{T_F} \tag{5.13}$$

5.2.3 Fixed Line Rate System

The scan rate for a line period, T_L, is

$$R_S \geq \frac{M N_{E,L}}{T_L} \tag{5.14}$$

where $N_{E,L}$ = number of edges transmitted per line.

The transmission rate is

$$R_B = \frac{N_{B,E} N_{E,L}}{T_L} \tag{5.15}$$

5.3 Selection of System Parameters

The type of edge detection system to be utilized in some application will be selected on the basis of cost, size, weight, ease of implementation, etc. as a function of the bandwidth reduction capability desired. Upon specification of the type of edge detection system, the system parameters will be determined according to the following procedure:

(1) The number of video amplitude bits per edge, A, is chosen to yield an acceptable grey scale rendition for the class of pictures to be transmitted.

(2) The optimum maximum run length, M, and hence number of edge position bits, G, is chosen for the value of the probability of an edge occurrence, p, most widely representing the class of pictures.

(3) For the set (A, G, Q) there is a value of the number of edges transmitted per second which will make underscanning or edge threshold degradation unobjectionable for fixed frame rate or fixed line rate systems.

(4) For the set (A, G, Q) the probability of transmission error is set to make the effect of transmission errors acceptable.

5.4 Bandwidth Reduction Factor

For systems operating with a fixed line rate or fixed frame rate it is possible to specify a meaningful bandwidth reduction factor for a compressed bandwidth television system in comparison with a conventional uncompressed digital television system only if all other measures of picture quality are equal. Spatial resolution, grey scale rendition, image motion blur and other operating parameters of stop-scan edge detection systems and a conventional digital system are relatively easy to compare since these effects are common to both systems. However, the effects of underscanning and edge position transmission errors are peculiar to the edge detection systems. It appears that the only practical way of comparison is to adjust the parameters of the edge detection systems so that the effects of underscanning and transmission errors are not objectionable to a consensus of viewers.

With systems operating with a variable frame rate the effect of underscanning is not present; however, the effect of transmission errors must be considered. A basic problem in comparing the bandwidth reduction capability of an edge detection system operating in a variable frame rate mode and a conventional system is that the picture transmission time period of the two systems is not necessarily equal. In order to make the bandwidth reduction factor meaningful in this case it will be assumed that a large number of pictures are to be transmitted by the systems; and that due to the statistical regularity of picture detail over a large number of pictures, it will be possible to set the parameters of the edge detection system to provide nearly equal average picture transmission rates.

In all situations the bandwidth comparison of the edge detection systems to a conventional digital television system are made on the basis of equal quality for represented pictures as determined subjectively. Operating in this manner the edge detection systems require a somewhat smaller probability of bit detection error for transmission. The consequence of this in terms of channel capacity and transmitted power is considered in the next section.

Table 5-1 gives expressions for the bandwidth reduction factors for the family of edge detection systems in terms of the edge transmission rate. The expressions are given as the ratio of the number of bits required to code a television source by conventional pulse code modulation, to the number of bits required to code the edges of the source. An explanation of the terms in the expressions is given in the glossary.

Estimates of the bandwidth reduction capability of the edge detection systems is given in table 5-2. The estimates are for a 384 × 384 element picture with a probability of edge occurrence of p = .1 for basic edge detection.

5.5 Information Transmission Capability

Edge detection systems provide a substantial bandwidth reduction over conventional digital television transmission; however,

TABLE 5-1

BANDWIDTH REDUCTION FACTORS OF EDGE DETECTION SYSTEMS

System	Bandwidth Reduction Factor
Variable Frame Rate Interframe Edge Coding	$BWR = \frac{(N_{B,D})(N_{D,F})}{(N_{B,E})(\overline{X}_F)}$
Fixed Frame Rate - Interframe Edge Coding	$BWR = \frac{(N_{B,D})(N_{D,F})}{(N_{B,E})(N_{E,F})}$
Fixed Line Rate - Interframe Edge Coding	$BWR = \frac{(N_{B,D})(N_{D,L})}{(N_{B,E})(N_{E,L})}$

System	Bandwidth Reduction Factor
Fixed Frame Rate - Frame Difference Coding	$BWR = \frac{(N_{B,D})(N_{D,F})(N_{F,Q})}{(N_{B,E,R})(N_{E,F,R}) + (N_{B,E,D})(N_{E,F,D})(N_{F,Q}-1)}$
Fixed Line Rate - Frame Difference Coding	$BWR = \frac{(N_{B,D})(N_{D,L})(N_{F,Q})}{(N_{B,E,R})(N_{E,L,R}) + (N_{B,E,D})(N_{E,L,D})(N_{F,Q}-1)}$

TABLE 5-2

ESTIMATES OF BANDWIDTH REDUCTION FACTORS

	Variable Frame Rate System		Fixed Frame Rate System		Fixed Line Rate System	
Basic Stop-Scan Edge Detection System	6.3	14,750	6.1	15,100	4.3	56
Line Correlation Stop-Scan Edge Detection System	6.9	11,800	6.8	12,100	4.7	45
Vector Correlation Stop-Scan Edge Detection System	7.6	8,850	7.4	9,060	5.2	34
Frame Difference Stop-Scan Edge Detection System	-	-	15.5	5,000	10.6	19
	BWR	$\overline{X}_F$	BWR	$N_{E,F}$	BWR	$N_{E,L}$

NOTE: Bandwidth reduction referenced to five bit per sample PCM coding.

for equivalent picture quality a somewhat lower bit error probability is required. In some communication applications, system bandwidth may be the prime consideration, and the required lower value of the bit error may be accommodated by an increase in transmitted signal power. In other types of applications it will be the transmitter power that must be conserved. Reducing the system bandwidth reduces the receiver noise, and therefore, by itself bandwidth reduction permits a lowering of the transmitter power. It will now be shown that the incremental increase in transmitter power required to lower the bit error probability is more than offset by the decrease in transmitter power made possible by the bandwidth reduction.

In any digital communication system the bit error probability, P_e, can be related directly to the system signal-to-noise ratio, $(\frac{S}{N})$.

For example, in a frequency shift keying incoherent communication system the relationship is[1]

$$P_e = \frac{1}{2} \exp \left\{ -\frac{1}{2}\left(\frac{S}{N}\right) \right\} \tag{5.16}$$

For this communication system a decrease in the probability of error from 10^{-3} to 10^{-5} requires about a 2 db increase in signal power.

---

[1] J. G. Lawton, "Comparison of Binary Data Transmission Systems," Second National Convention on Military Electronics (1958).

However, a decrease in bandwidth by a factor of 5 allows a decrease in required transmitter power by about 7 db. Thus, for equivalent picture quality it is possible to transmit television with 5 db less power with the basic edge detection system than with conventional pulse code modulation.

CHAPTER 6

STATISTICAL IMAGE MEASUREMENTS

Measurements of the number of edges have been made for the four scenes illustrated in exhibit 6-1. All measurements were made with the experimental television bandwidth reduction system operating in a continuous scanning mode. The spatial resolution was 372 active elements per line and 384 active lines per frame. The edge threshold was 15 percent the maximum video amplitude. A list of the number of edges detected per line and frame is given in table 6-1 for the four scenes.

TABLE 6-1

EDGE COUNT OF FOUR SCENES

Measurement	Photo 1	Photo 2	Photo 3	Photo 4
Number of Edges per Line	21	62	66	70
Number of Edges per Frame	8,730	21,700	24,700	29,000

EXHIBIT 6-1

SCENES USED IN STATISTICAL IMAGE MEASUREMENTS

Plate 1

<u>Photo 1</u>

Black and White Bar Chart

<u>Photo 2</u>

Moon

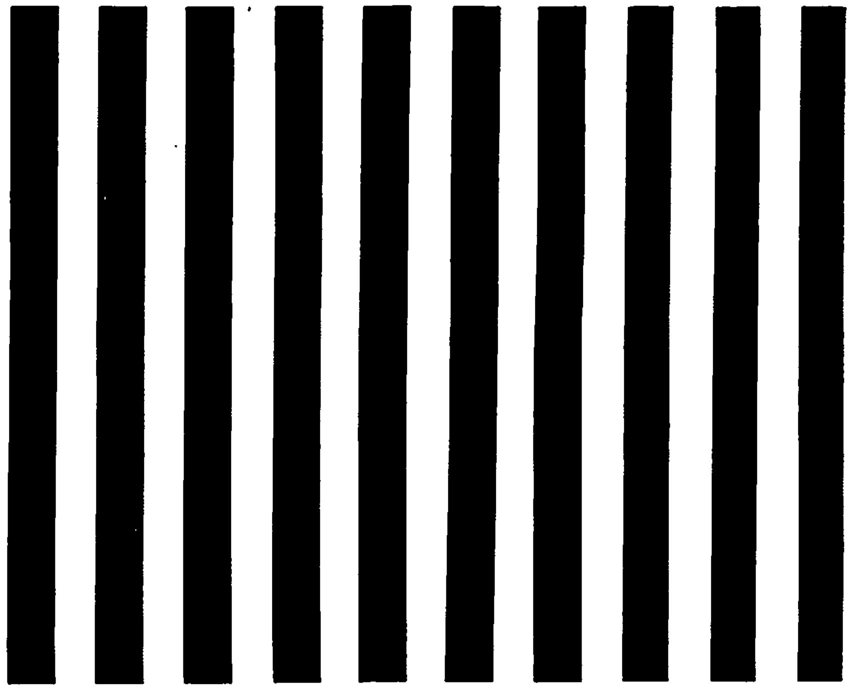


PHOTO 1

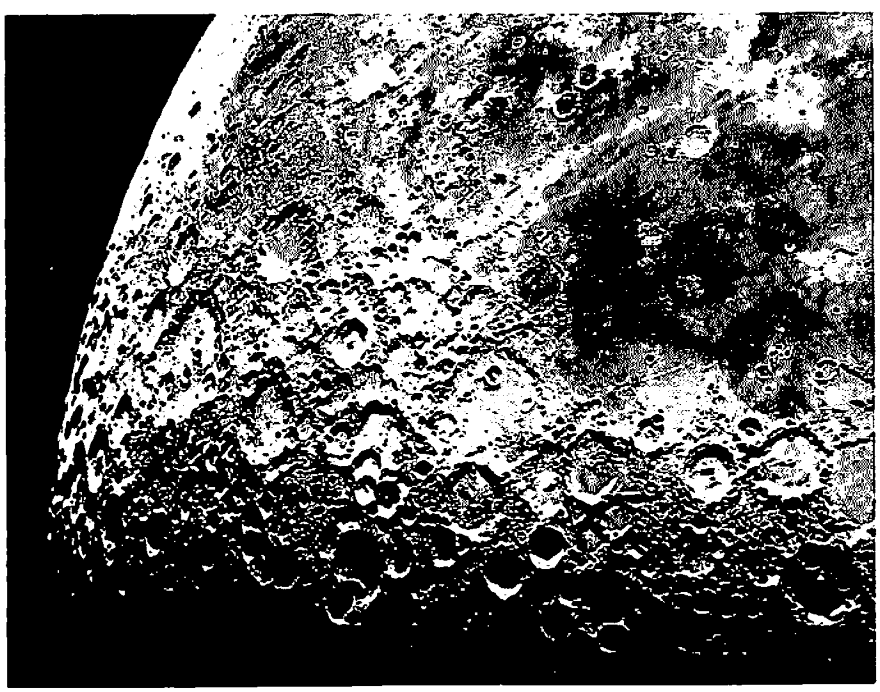


PHOTO 2

EXHIBIT 6-1

SCENES USED IN STATISTICAL IMAGE MEASUREMENTS

Plate 2

Photo 3

Olin Hall

Photo 4

Engineering Quadrangle

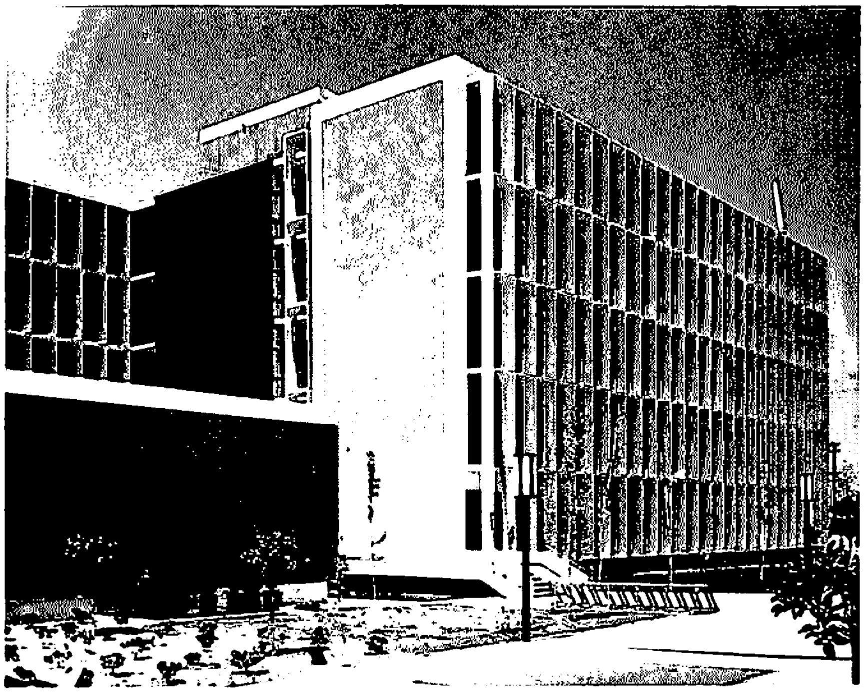


PHOTO 3

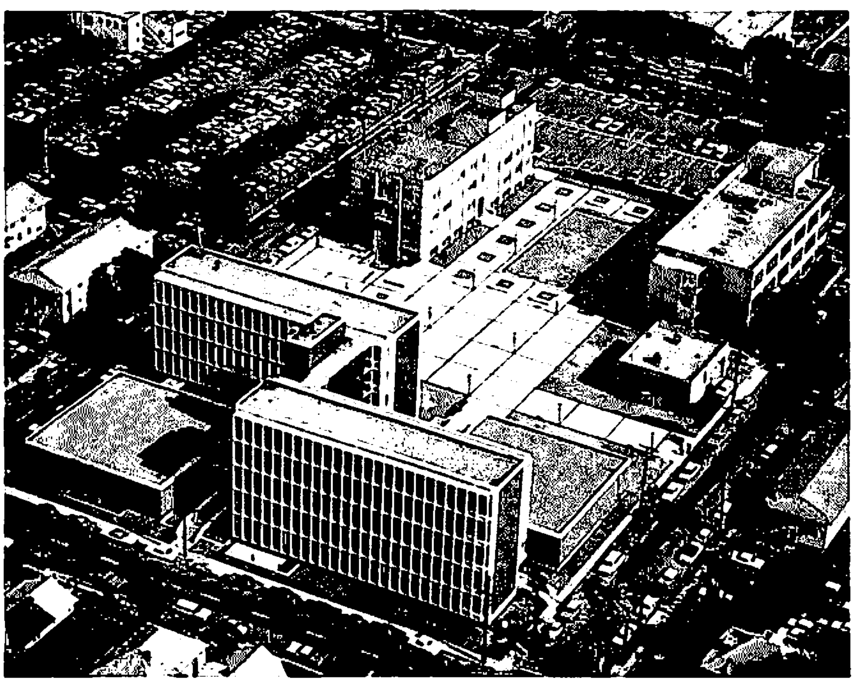


PHOTO 4

CHAPTER 7

IMPLEMENTATION OF BASIC STOP-SCAN EDGE DETECTION SYSTEM

This chapter presents a discussion of the implementation of the basic stop-scan edge detection system. The vehicle for this discussion is the experimental system equipment illustrated in Exhibit 7-1.

7.1 Experimental System Description

Detailed block diagrams of the transmitting and receiving units of the experimental multilevel system are shown in figures 7-1 and 7-2. Table 7-1 defines the systems parameters. Appendix IV contains the logic equations for the system.

7.1.1 Stop-Scan Camera

The stop-scan camera for the edge detection system must be capable of highly accurate stepped scanning, and must generate pulsed video upon external command. The latter requirement can be met by a pulsed video amplifier. Accurate step scanning is feasible only with electrostatic beam deflection. The more widely used form of electromagnetic scanning used in commercial cameras requires

EXHIBIT 7-1

EXPERIMENTAL SYSTEM EQUIPMENT

Plate 1

Photo 1

Stop-Scan Camera

Photo 2

Stop-Scan Monitor

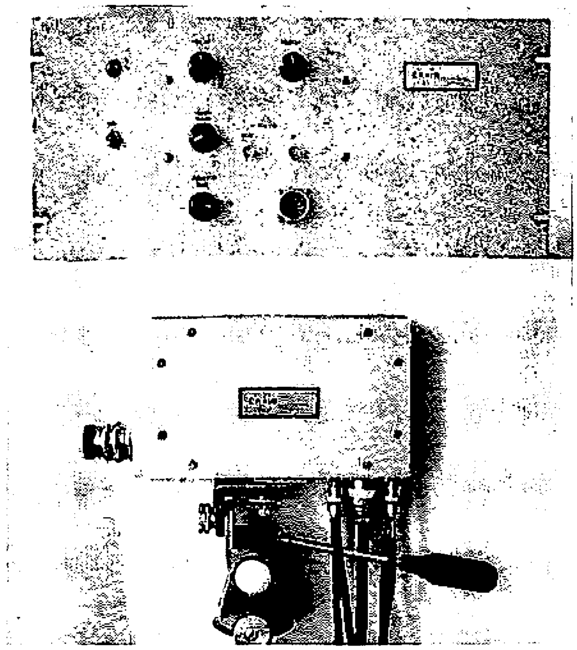


PHOTO 1

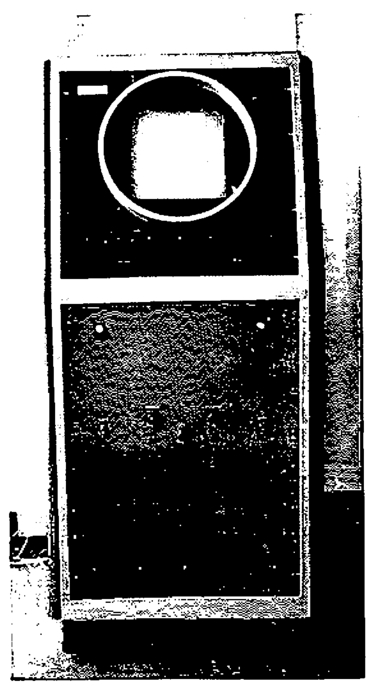


PHOTO 2

EXHIBIT 7-1

EXPERIMENTAL SYSTEM EQUIPMENT

Plate 2

Photo 3

Coder and Decoder

Photo 4

Logic Modules

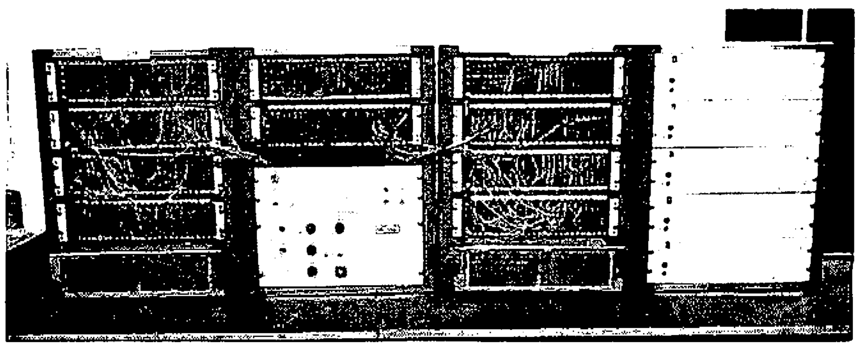


PHOTO 3

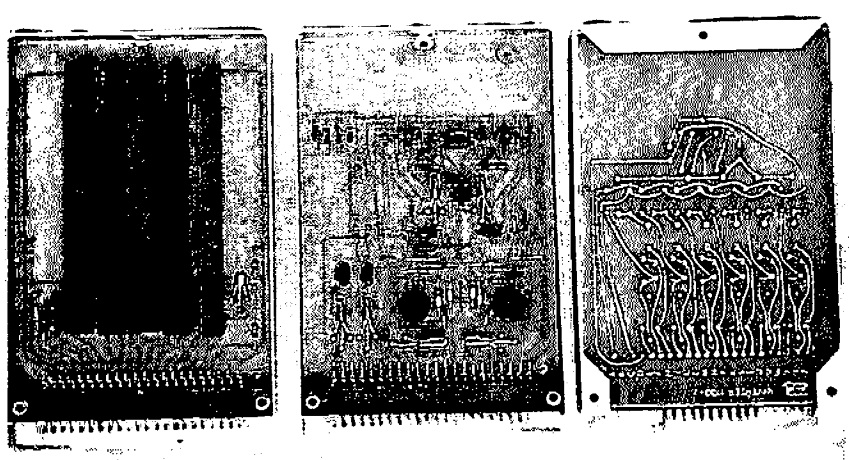


PHOTO 4

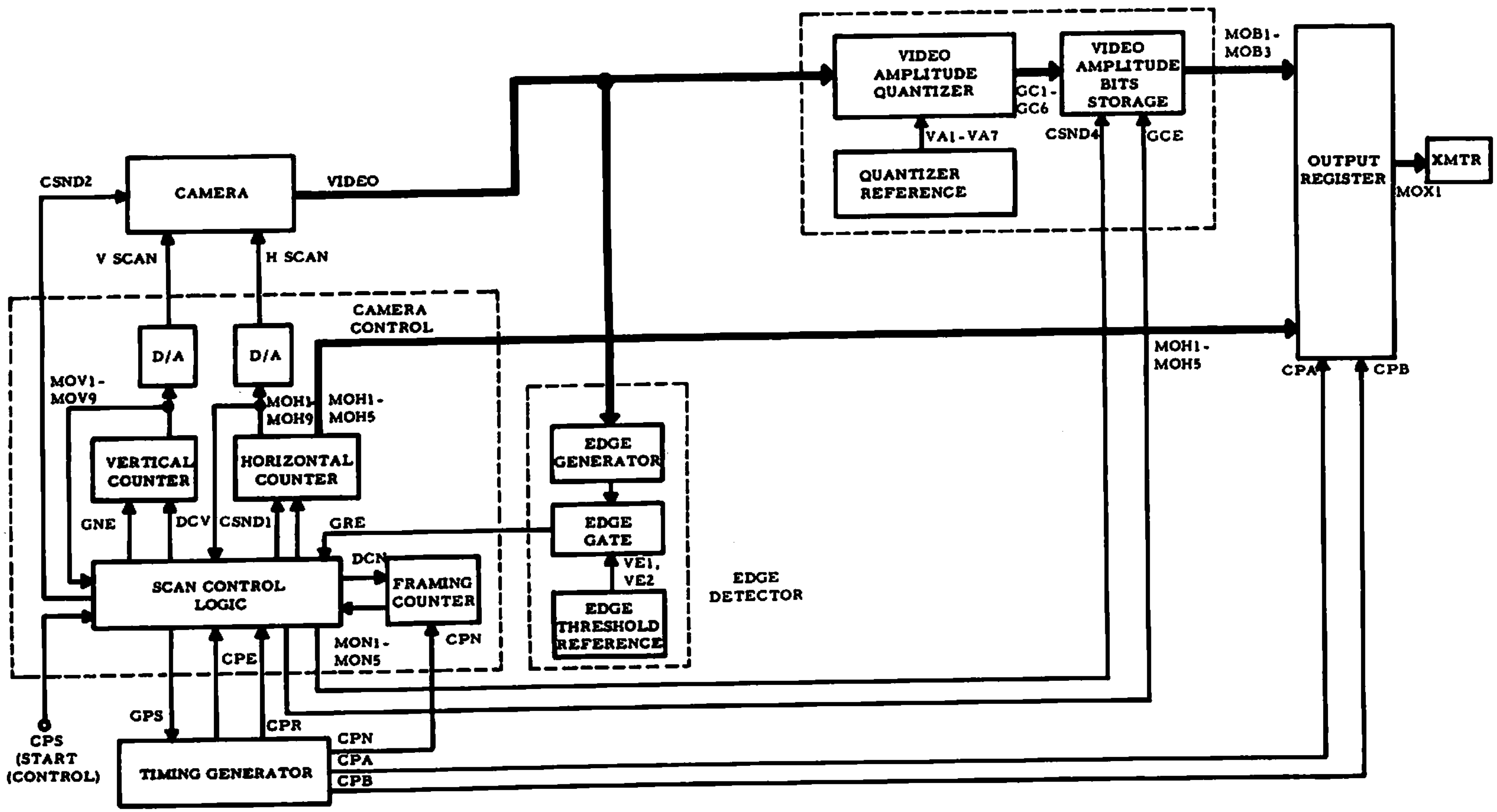


Figure 7-1. --Transmitting unit of experimental system

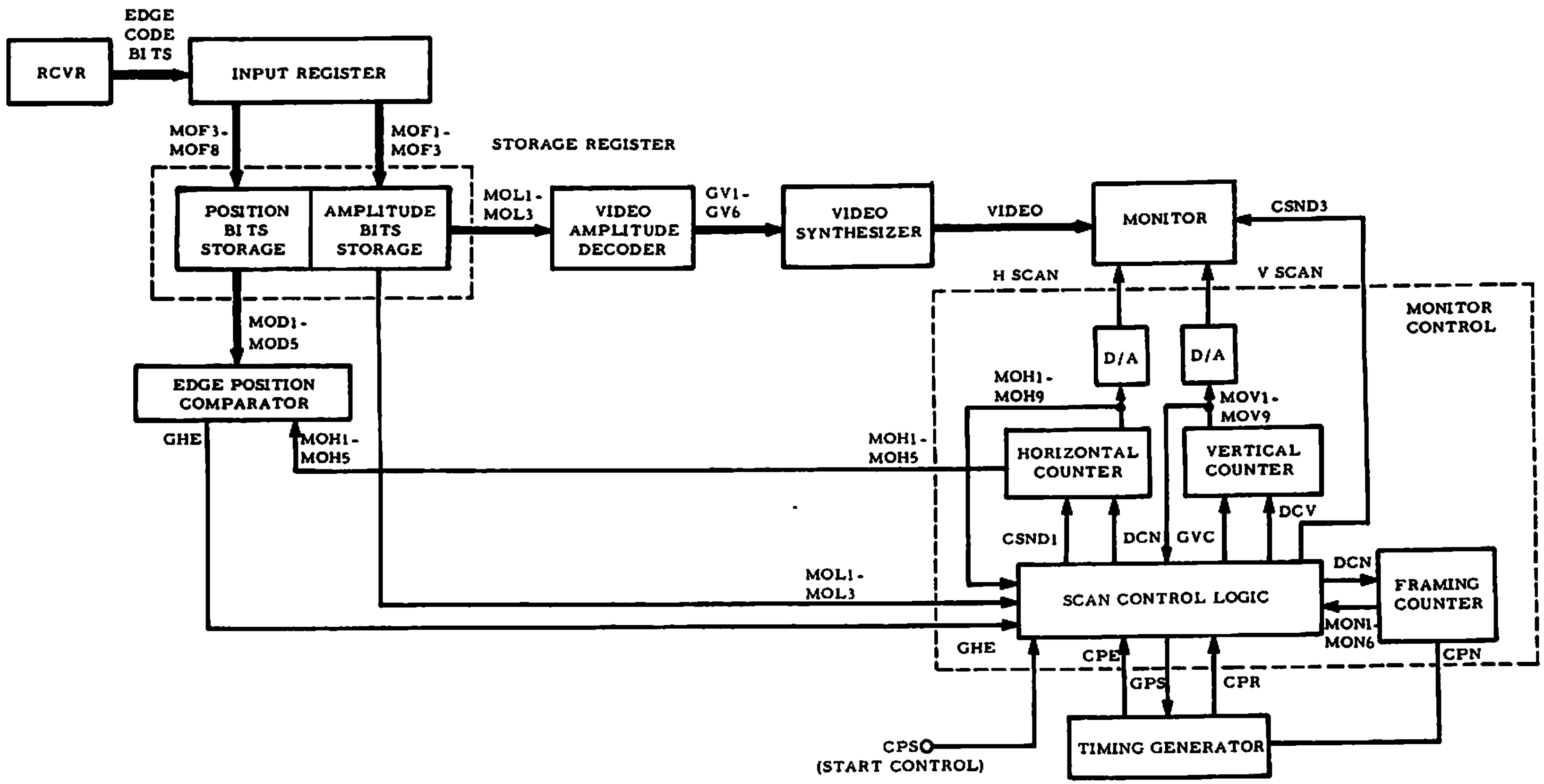


Figure 7-2. --Receiving unit of experimental system

TABLE 7-1

PARAMETERS OF EXPERIMENTAL SYSTEM

Edge Definition:	Non-adjacent edge detection (delay line edge generator)
Edge Composition:	5 position bits, 3 amplitude bits
Edge Transmission Capability:	31 edges, 1 synch per line
Scanning Rate Mode:	Fixed line rate
Frame Size:	384 lines, 384 elements per line
Frame Rate:	5 frames per second
Retrace Mode:	12 element horizontal blanking, no vertical blanking

many amperes of current to be driven through the camera deflection coils. The control of this magnitude of current to produce a deflection accuracy of better than one camera resolution element is impractical.

Figure 7-3 illustrates the block diagram of the experimental stop-scan camera. Horizontal and vertical scan voltages from the camera control unit are fed to amplifiers which drive the deflection plates of a vidicon camera tube. If neither of the scan voltages are present a safety beam interlock switch prevents the beam from being

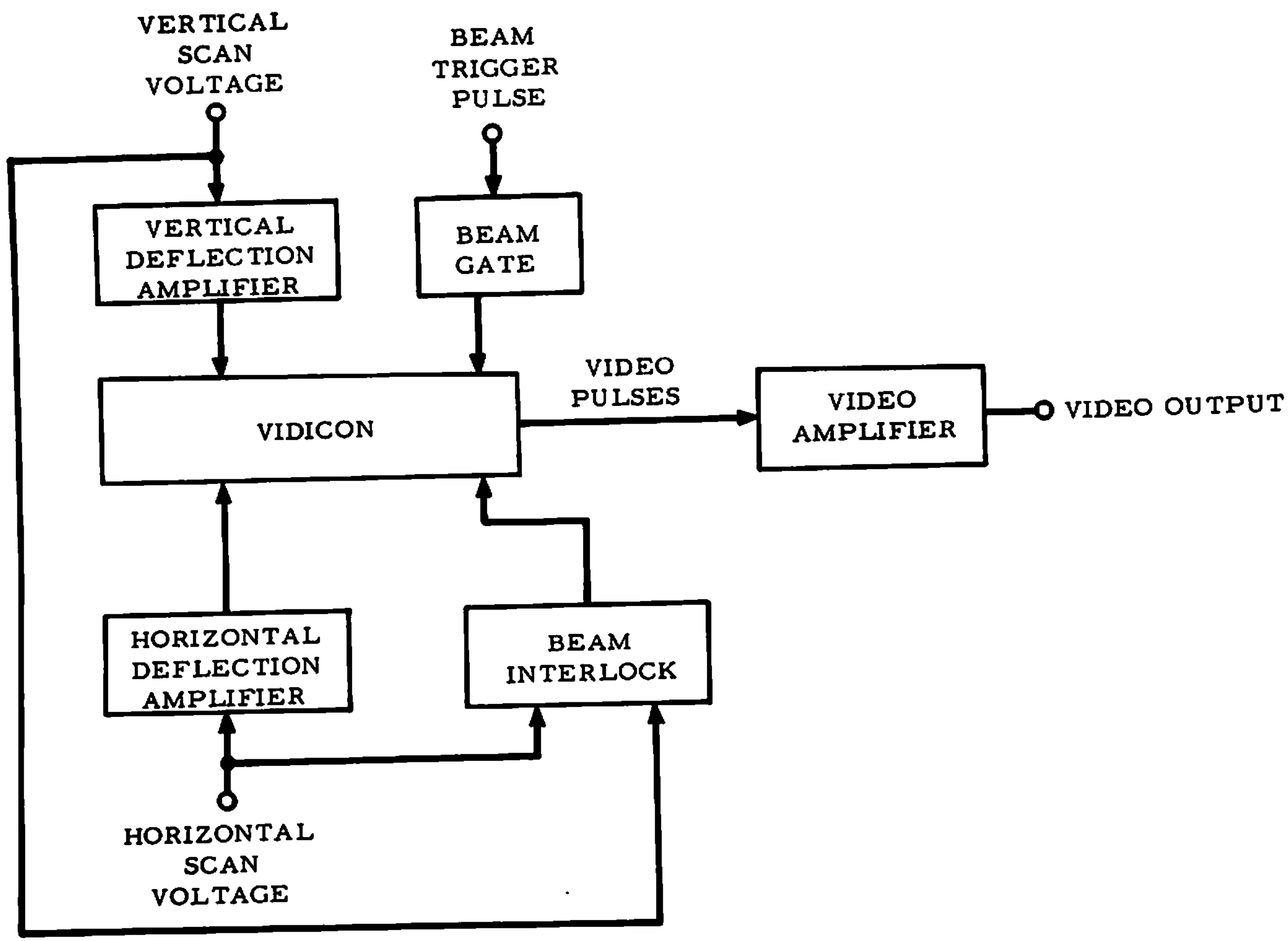


Figure 7-3. --Stop-scan camera

gated on, and thus prevents damage to the vidicon. The beam trigger pulse triggers a one-shot multivibrator in the beam gate unit to switch on the vidicon beam and sample the brightness of a vidicon element. The video pulses are amplified and transferred to the edge detector and video amplitude coder.

7.1.2 Stop-Scan Monitor

The stop-scan monitor has essentially the same operational requirements as the stop-scan camera. The video input signal to the monitor is a series of asynchronous video pulses whose width correspond to the element dwell time of a standard television monitor.

Figure 7-4 shows a block diagram of the experimental stop-scan cathode ray tube monitor. The horizontal and vertical deflection units and the beam interlock unit operate in an identical fashion to their counterparts in the stop-scan camera. The incoming video signal from the video synthesizer is amplified to intensity modulate the cathode ray tube beam. When a beam trigger pulse is received a beam gate permits the beam to strike the cathode ray tube face to display a video element.

7.1.3 Timing Generator

The timing relations of the transmitter and receiver timing generators are given in table 7-2.

Pulse CPO generates pulses CPA and CPB to drive the output

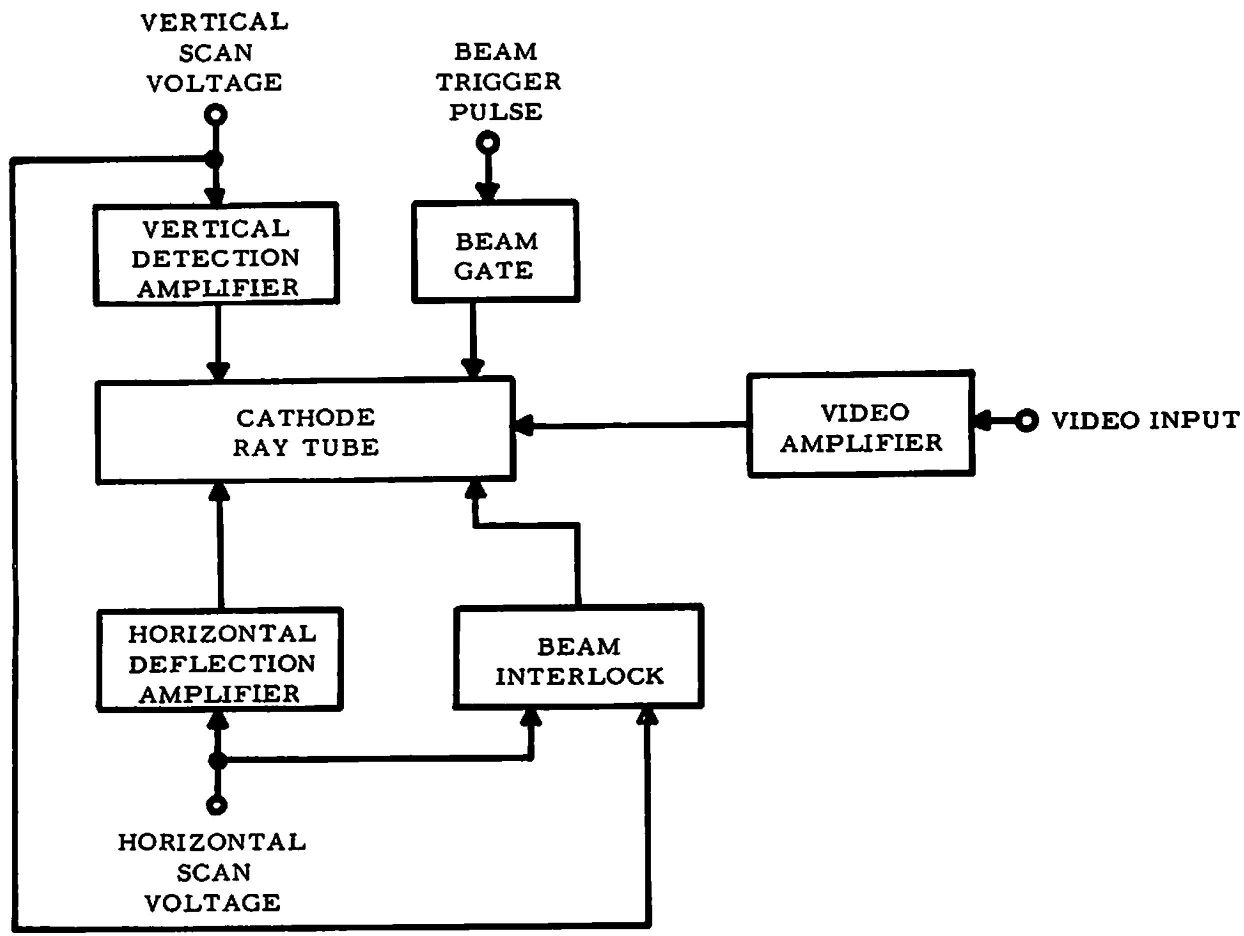


Figure 7-4. --Stop-scan monitor

TABLE 7-2

TIMING RELATIONS

Clock Pulse	Rate
CPE - element scan pulse	-
CPR - edge readout pulse	$R_{CPR} = \frac{1}{32} R_{CPE}$
CPO - edge bit rate pulse	$R_{CPO} = \frac{1}{4} R_{CPE}$

register. When CPA occurs, edge code bits are transferred in parallel to the output register. Seven CPB pulses then occur in the interval between CPA pulses to shift the contents of the output register serially to the transmitter.

7.1.4 Camera and Monitor Control

In the camera and monitor control units the position of the camera beam and monitor beam is controlled by the state of horizontal and vertical scan counters. The counter states are converted to analog voltages to drive the camera and monitor deflection amplifiers. The conversion is performed by a binary voltage weighter type of digital-to-analog converter.

A timing diagram of the camera scan control system is shown in figure 7-5. In the diagram an edge occurrence is assumed at

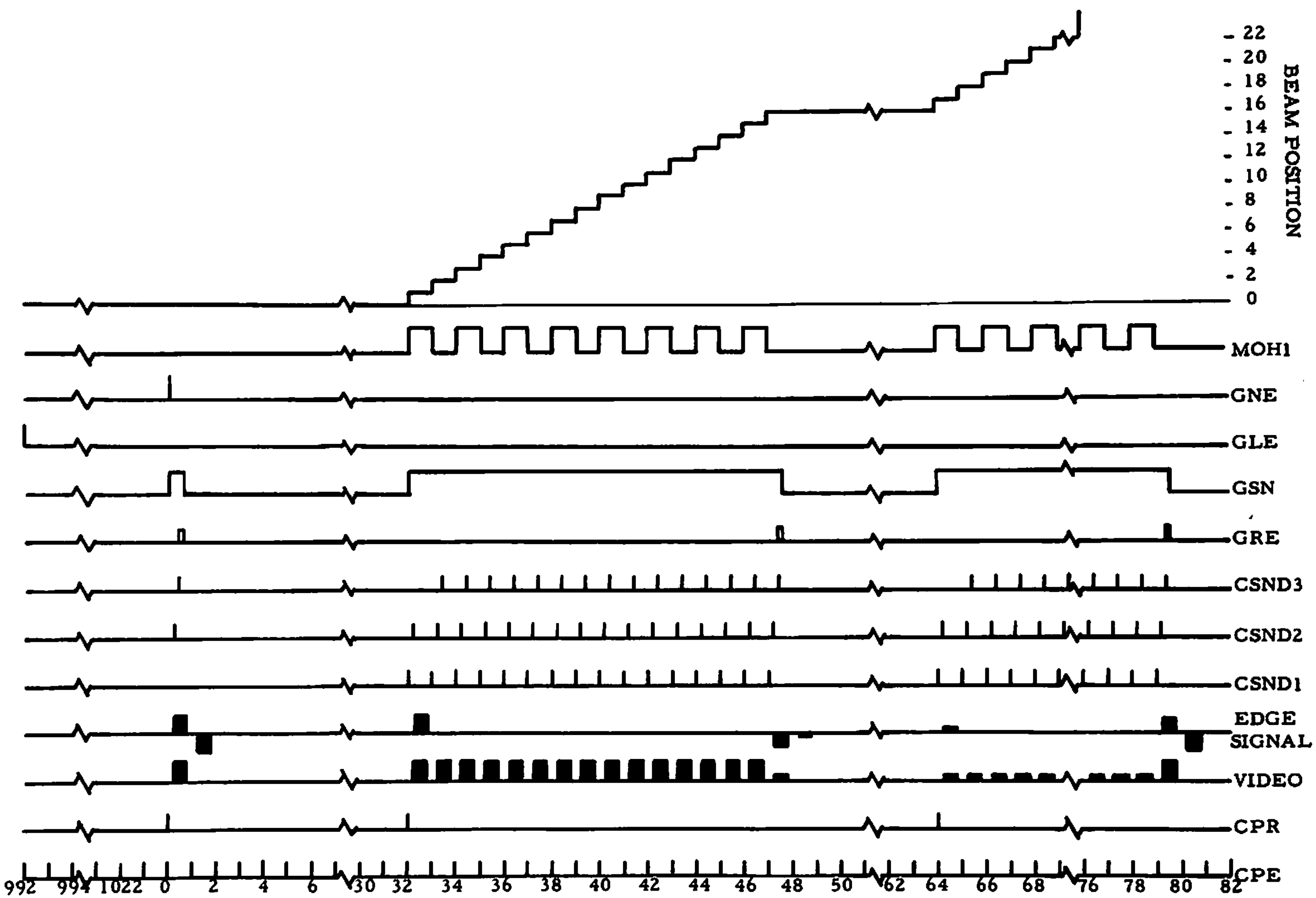


Figure 7-5. --Stop-scanning example

every sixteenth element scanned. The scan pulses perform functions stated in table 7-3.

TABLE 7-3

SCAN PULSE FUNCTIONS

Camera Control Unit		
CSND1	-	Advance horizontal scan counter
CSND2	-	Trigger camera beam
CSND3	-	Sample edge signal
CSND4	-	Sample video signal
Monitor Control Unit		
CSND1	-	Advance horizontal scan counter
CSND2	-	Trigger monitor beam
CSND3	-	Check edge comparator coincidence

In the coder, scan pulses CSND2, CSND3, and CSND4 are delayed with respect to CSND1 to allow for circuit delays. Since the coder utilizes the delay line edge detection technique, true edges will only be formed after two elements are scanned consecutively in time. Thus, whenever scanning is resumed after an edge has been transmitted, CSND3 must be inhibited for the first occurrence of CSND2.

This prevents the generation of a false edge.

When the scan beam has sampled 372 video elements or the active line time has elapsed, control level GDE resets the horizontal scan counter to its zero state. At the end of the line blanking period the first video element to be sampled is in a position corresponding to the zero state of the counter. The first occurrence of CSND1 must be inhibited at the beginning of a line to prevent the horizontal scan counter from advancing until the camera beam is triggered at the first horizontal scan position.

7.1.5 Video Amplitude Coder and Decoder

In the video amplitude coder, video pulses are quantized directly by a series of quantizer switches. If the video signal amplitude exceeds a quantizer switch reference voltage, the quantizer output assumes a logic one state; otherwise it remains in the logic zero state. A set of logic gates then transform the states of the quantizer switches into signals which set or reset video amplitude bits storage flip-flops. The quantization levels and states of the video amplitude storage flip-flops are listed in table 7-4. The synchronization signal is coded as the all "ones" state of the flip-flops.

At the video amplitude decoder, the amplitude bits stored in the storage register are directly decoded by gates which detect the code pattern corresponding to each video quantum level. The decoded gate signals then are amplified and weighted to produce the proper reconstructed video amplitude level.

TABLE 7-4

VIDEO AMPLITUDE CODING LOGIC

Quantizer Switch Input Condition	Quantizer Switch Output State	Video Amplitude Bits MOB1	MOB2	MOB3
$V_S > V_1$	GC1 = 0	0	0	0
$V_S < V_1$	GC1 = 1	0	0	1
$V_S < V_2$	GC2 = 1	0	1	1
$V_S < V_3$	GC3 = 1	0	1	0
$V_S < V_4$	GC4 = 1	1	1	0
$V_S < V_5$	GC5 = 1	1	0	0
$V_S < V_6$	GC6 = 1	1	0	1
Synchronization Code		1	1	1

7.1.6 Edge Detector

A block diagram of the delay line edge detector is shown in figure 7-6. Each video pulse is delayed by one element scan time, and subtracted from the next video pulse. If the difference signal

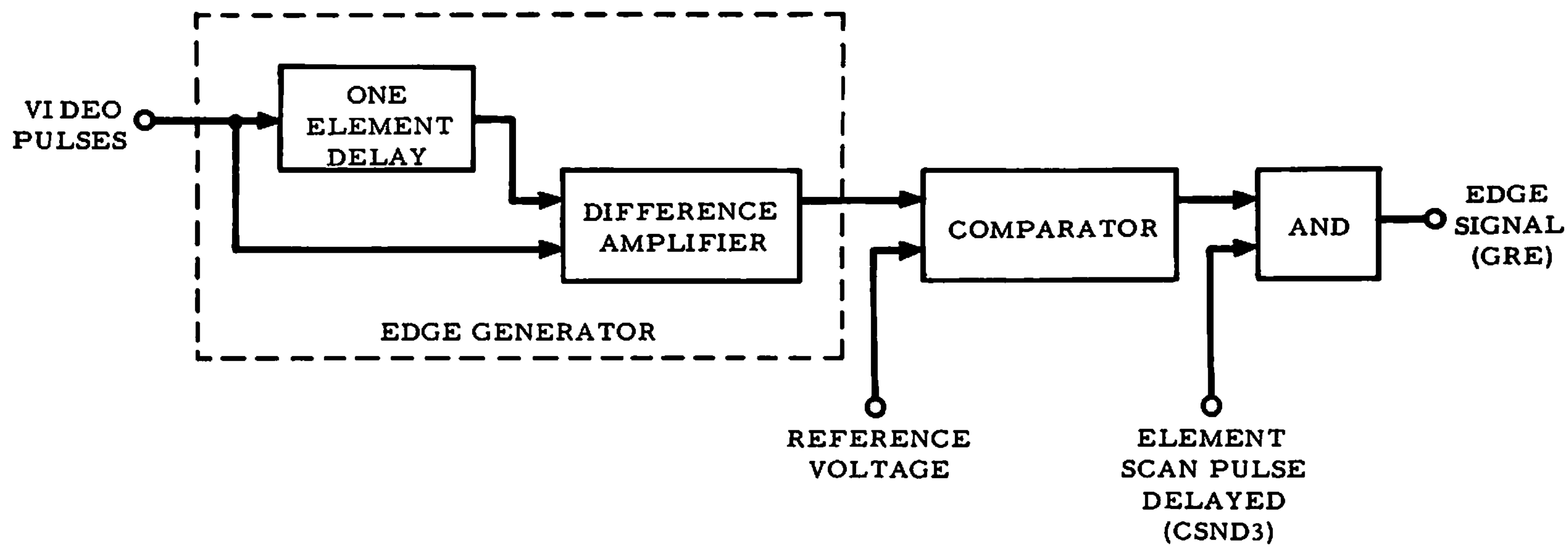


Figure 7-6. --Delay line edge detector

exceeds the reference voltage in coincidence with the delayed element scan pulse CSND3, an edge indication GRE is produced.

7.2 Digital Systems Experiments

The digital coding and decoding portions of the experimental system were tested by supplying an artificial video signal to the system to generate a predicted display. The artificial video signal simulated the scanning of a vertical black and white bar chart with bars 16 elements apart.

For the systems tests the output register was connected directly to the input register. At the decoder the video synthesizer output signal modulated the Z-axis of a cathode ray oscilloscope which acted as a television monitor. The horizontal and vertical deflection voltages were H SCAN and V SCAN of the decoder.

Exhibit 7-2 contains a series of oscilloscope photographs taken of waveforms in the experimental system. Photo 25 shows a photograph of the display of the oscilloscope monitor.

The horizontal sweep voltage during continuous scanning is shown in detail in photo 6. A slight amount of ringing exists at the step transitions due to the inductance of the wiring and stray capacitance in the binary voltage weighter, horizontal counter bit driver circuits, and the camera cable. The ringing impairs the resolution of the video signal somewhat. A more compact design should make the ringing negligible.

EXHIBIT 7-2

DIGITAL SYSTEMS EXPERIMENTS

Plate 1

<u>Photo 1</u> 5 μsec/cm horizontal, 5 volt/cm vertical

1:CPA transmitter
2:CPB transmitter

<u>Photo 2</u> 100 μsec/cm horizontal, 5 volt/cm vertical

1:GN30 transmitter
2:GN31 transmitter

<u>Photo 3</u> 200 μsec/cm horizontal, 5 volt/cm vertical

1:GH371 transmitter, no edges
2:GH371 transmitter, artificial video signal

<u>Photo 4</u> 100 μsec/cm horizontal, 5 volt/cm vertical

1: ZOS2 transmitter, no edges
2:H SCAN transmitter, no edges

<u>Photo 5</u> 100 μsec/cm horizontal, 5 volt/cm vertical

1: ZOS2 transmitter, artificial video signal
2:H SCAN transmitter, artificial video signal

<u>Photo 6</u> 1 μsec/cm horizontal, 10 MV/cm vertical

1:H SCAN transmitter, artificial video signal

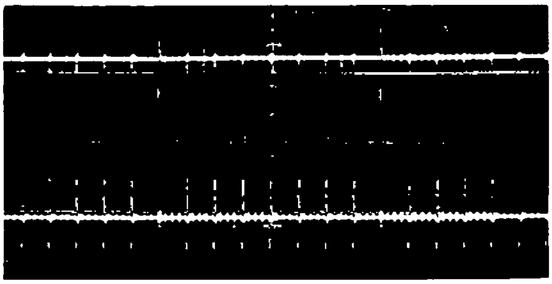


PHOTO 1

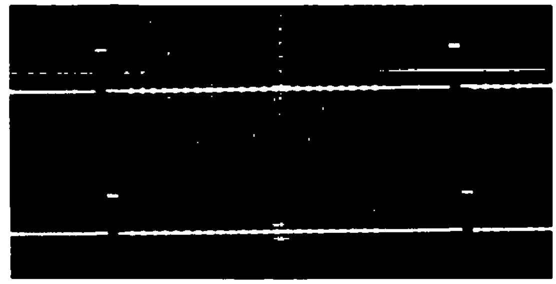


PHOTO 2

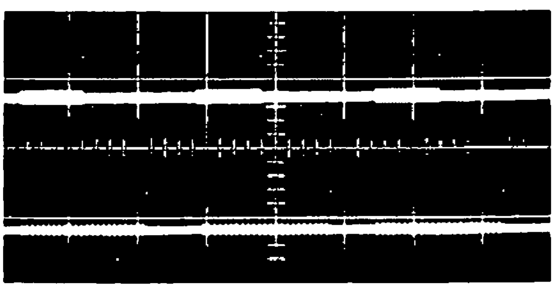


PHOTO 3

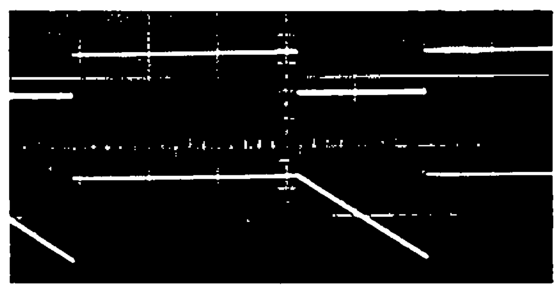


PHOTO 4

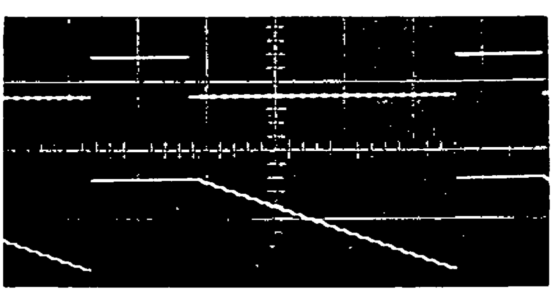


PHOTO 5

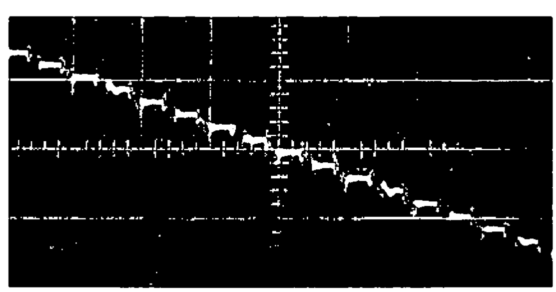


PHOTO 6

EXHIBIT 7-2

DIGITAL SYSTEMS EXPERIMENTS

Plate 2

5 volts/cm vertical

<u>Photo 7</u> 50 msec/cm horizontal

1:V SCAN transmitter

<u>Photo 8</u> 100 μsec/cm horizontal

1:ZOS1 transmitter
2:artificial video signal

<u>Photo 9</u> 100 μsec/cm horizontal

1:ZOH1 transmitter
2:artificial video signal

<u>Photo 10</u> 5 μsec/cm horizontal

1:ZOH1 transmitter
2:artificial video signal

<u>Photo 11</u> 5 μsec/cm horizontal

1:edge signal
2:artificial video signal

<u>Photo 12</u> 5 μsec/cm

1:GRE transmitter
2:artificial video signal

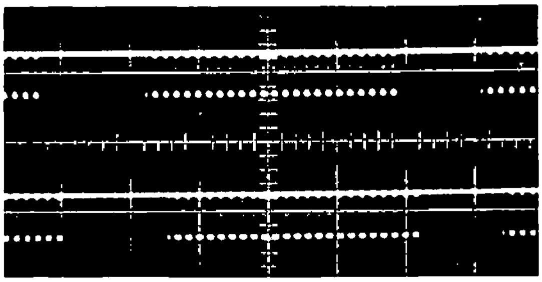


PHOTO 19

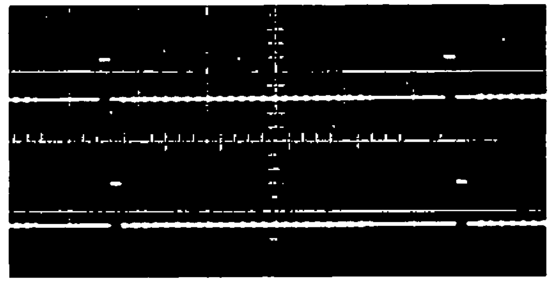


PHOTO 20

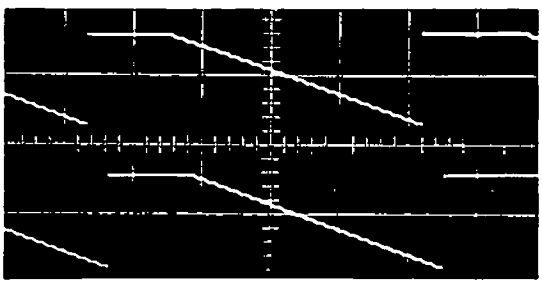


PHOTO 21

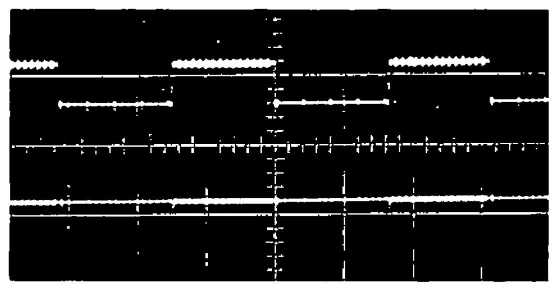


PHOTO 22

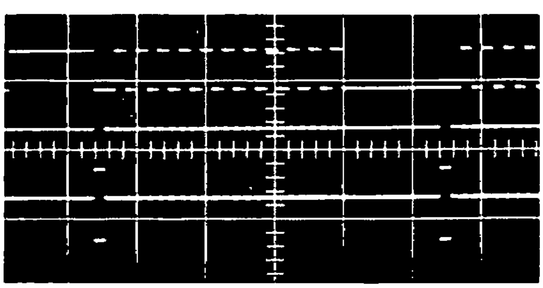


PHOTO 23

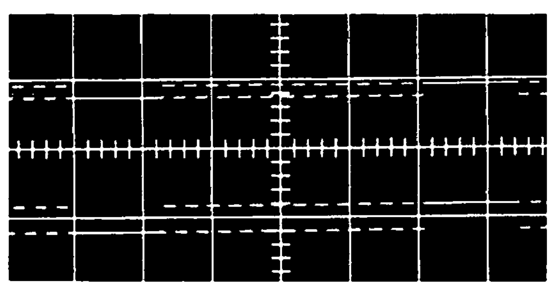


PHOTO 24

EXHIBIT 7-2

DIGITAL SYSTEMS EXPERIMENTS

Plate 5

Photo 25

Display on Oscilloscope Monitor, Artificial Video Signal

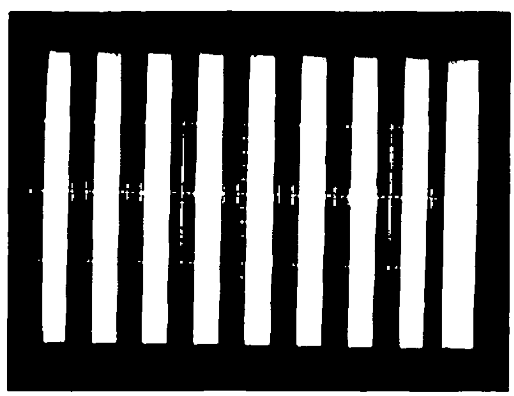


PHOTO 25

7.3 Stop-Scan Camera Experiments

The stop-scan camera was tested by scanning rear lighted positive film plates of a gray scale chart and a bar chart with vertical black and white bars. Exhibit 7-3 contains photographs of the stop-scan camera video signal with and without stop-scanning. The stop-scan process did not appear to distort the video signal waveform.

7.4 Stop-Scan Monitor Experiments

The stop-scan monitor was tested by operating the stop-scan camera and monitor as a closed circuit television system. Exhibit 7-4 contains photographs of test patterns and charts displayed on the stop-scan monitor.

7.5 Edge Detection Experiments

Figure 7-7 contains a schematic drawing of the edge generator circuit of the experimental delay line edge detector. The circuit delays each video pulse received by the maximum pulse repetition period, and subtracts the delayed pulse from the next video pulse.

The video pulse and delayed video pulses are buffer amplified by the emitter followers employing transistors T_1 and T_2. The pulses are then fed to the difference amplifier comprised of transistors T_4 and T_5 which are driven by the constant current source of

EXHIBIT 7-3

STOP-SCAN CAMERA EXPERIMENTS

Photo 1 50 μsec/cm horizontal, 5 volt/cm vertical

One line of black and white bar chart without stop-scanning

Photo 2 50 μsec/cm horizontal, 5 volt/cm vertical

1 : One line of black and white bar chart with stop-scanning
2 : H SCAN transmitter

Photo 3 2 μsec/cm horizontal, 2 volt/cm vertical

One bar of black and white bar chart without stop-scanning

Photo 4 20 μsec/cm horizontal, 2 volt/cm vertical

One bar of black and white bar chart with stop-scanning

Photo 5 20 msec/cm horizontal, 5 volt/cm vertical

One frame of black and white bar chart without stop-scanning

Photo 6 20 μsec/cm horizontal, 2 volt/cm vertical

One line of gray scale chart

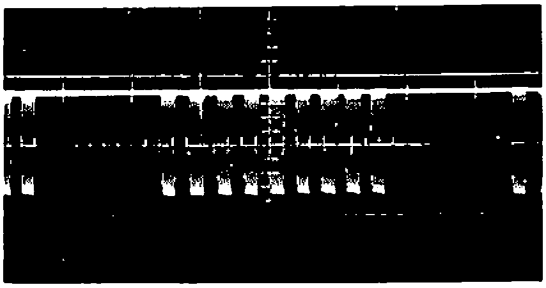


PHOTO 1

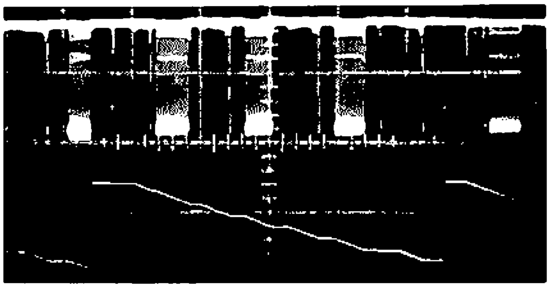


PHOTO 2

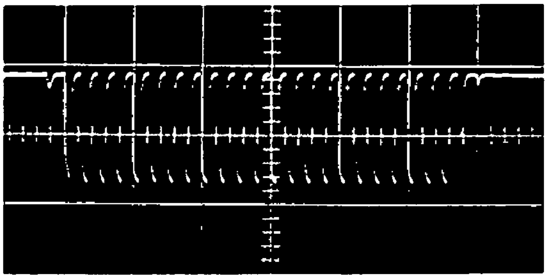


PHOTO 3

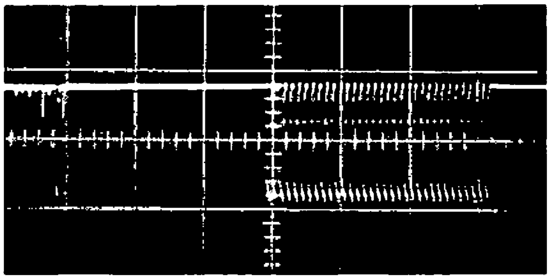


PHOTO 4

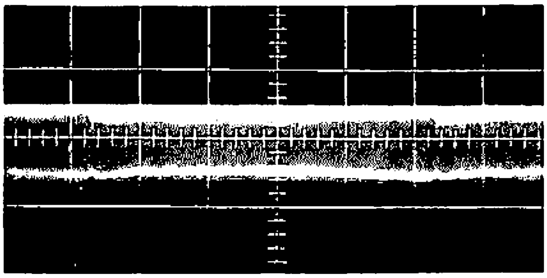


PHOTO 5

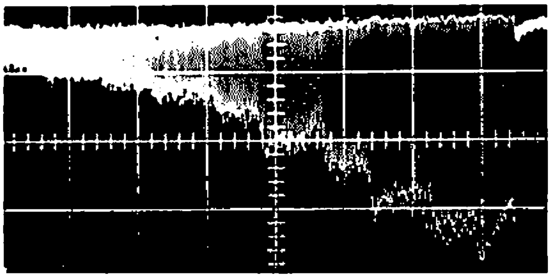


PHOTO 6

EXHIBIT 7-4

STOP-SCAN MONITOR EXPERIMENTS

Plate 1

<u>Photo 1</u>

Black and White Bar Chart

<u>Photo 2</u>

Video Modulation Chart

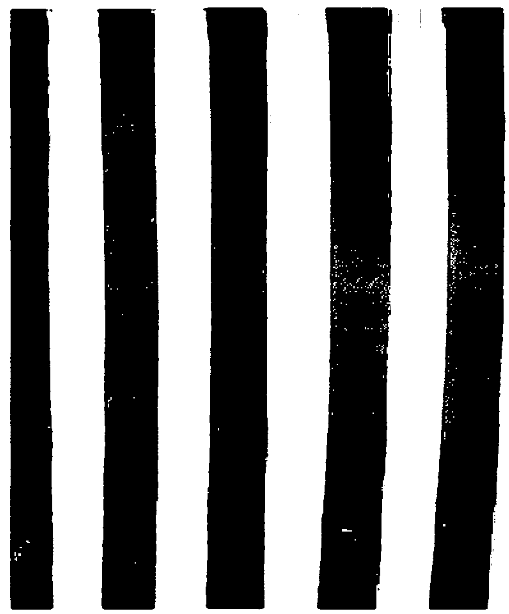


PHOTO 1

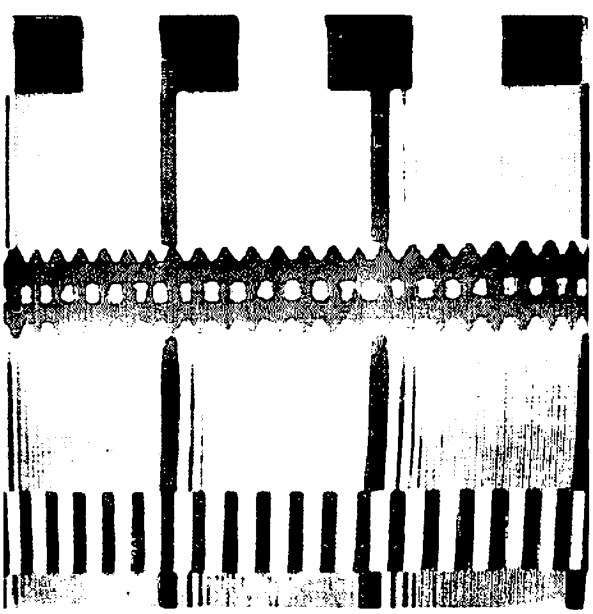


PHOTO 2

EXHIBIT 7-4

STOP-SCAN MONITOR EXPERIMENTS

Plate 2

<u>Photo 3</u>

RETMA Test Pattern

<u>Photo 4</u>

Grey Scale Test Chart

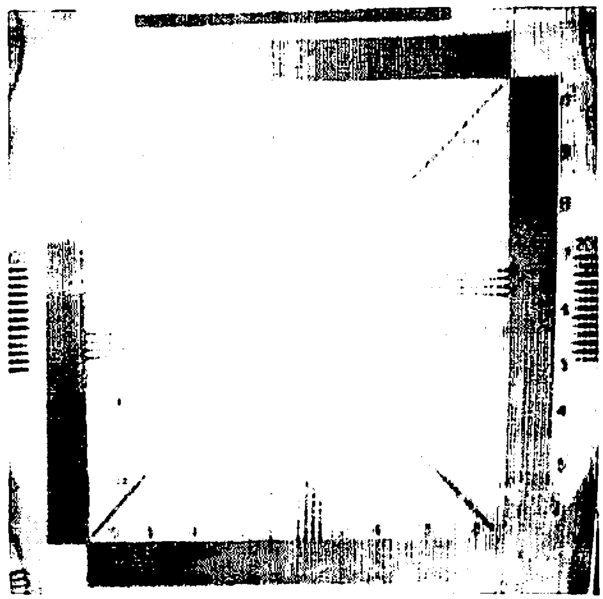
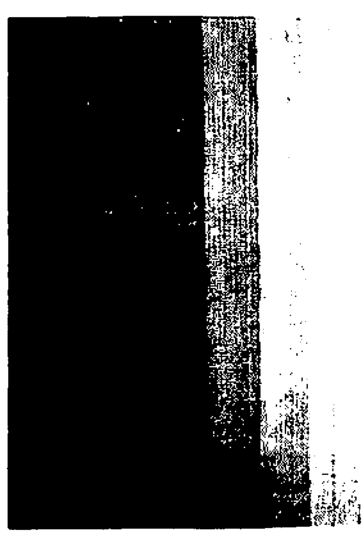


PHOTO 3



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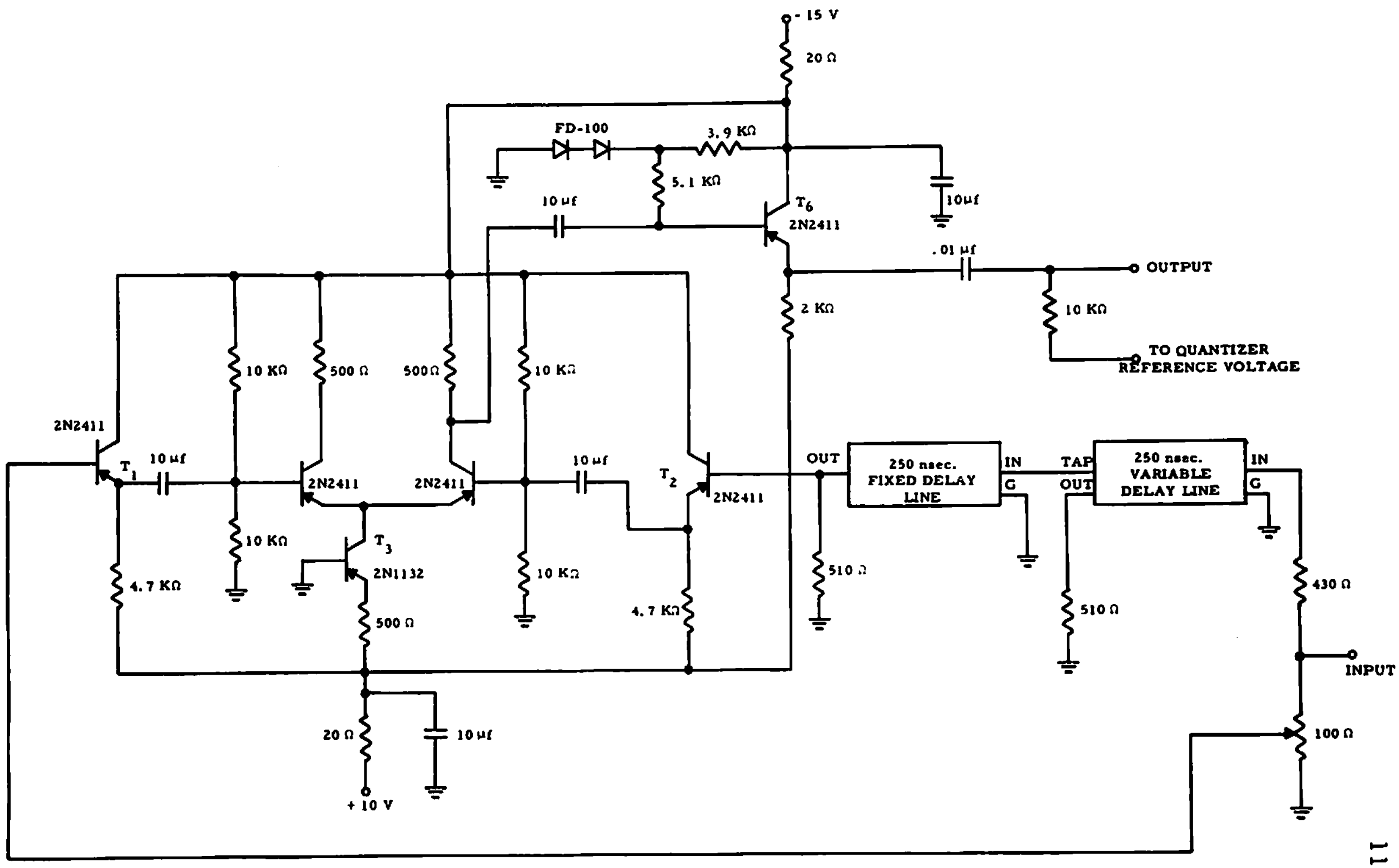

Figure 7-7. --Delay line edge generator

transistor T_3. The difference signal is then referenced to ground and buffer amplified by the emitter follower using transistor T_6.

Exhibit 7-5 illustrates oscilloscope photographs of the operation of the edge generator using test signals.

7.6 Video Synthesizer Experiments

The inputs to the video synthesizer are a set of six logical signals GV1 to GV6 which indicate the quantized level of the video signal. These signals are amplified and amplitude weighted according to the logarithmic quantization scale. The resultant signals AV1 to AV6 are then fed to the video summer circuit shown in figure 7-8.

In the circuit, the diode gate passes the most negative input signal. The video signal is then fed to an emitter follower for power amplification.

EXHIBIT 7-5

EDGE DETECTOR EXPERIMENTS

<u>Photo 1</u> 200 nsec/cm horizontal

1:output of delay line	.1 volt/cm vertical
2:input	.2 volt/cm vertical

<u>Photo 2</u> 200 nsec/cm horizontal, .1 volt/cm vertical

1:left input to difference amplifier
2:right input to difference amplifier

<u>Photo 3</u> 200 nsec/cm horizontal

1:output 2 volt/cm vertical
2:input .2 volt/cm vertical

<u>Photo 4</u> 500 nsec/cm horizontal

1:output 2 volt/cm vertical
2:input .1 volt/cm vertical

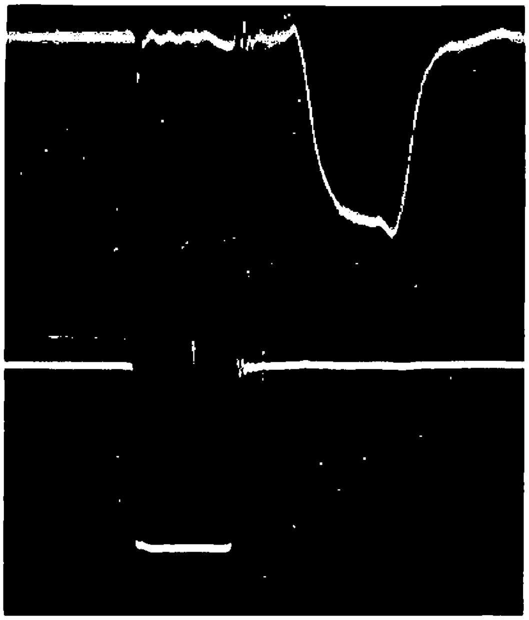

PHOTO 1

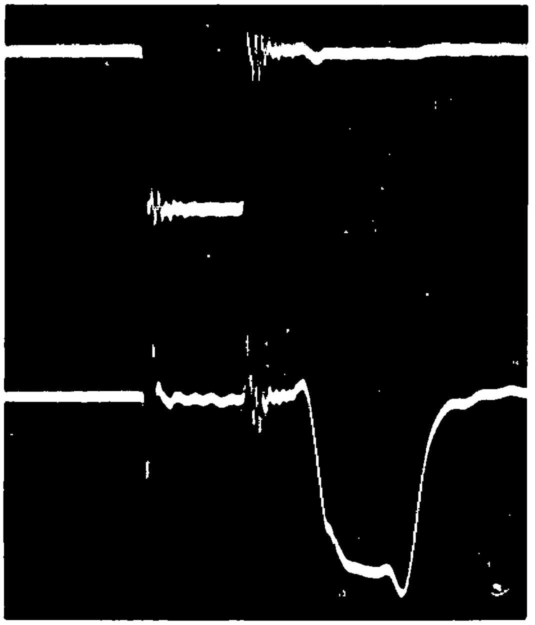

PHOTO 2

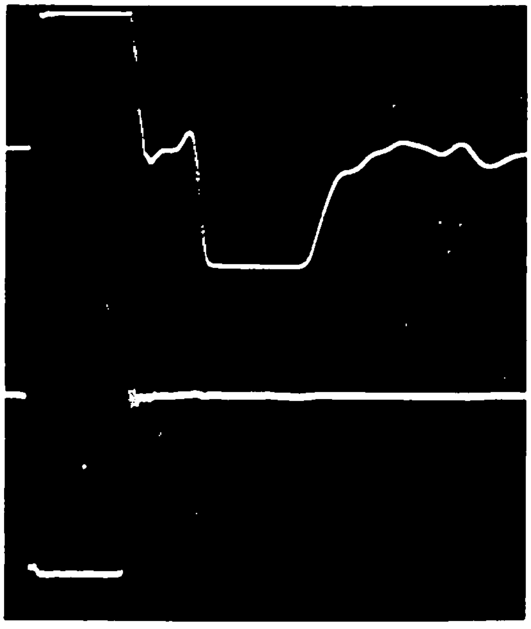

PHOTO 3

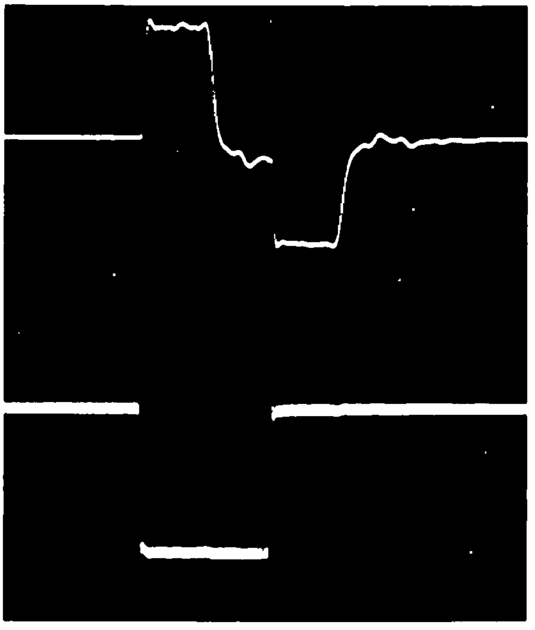

PHOTO 4

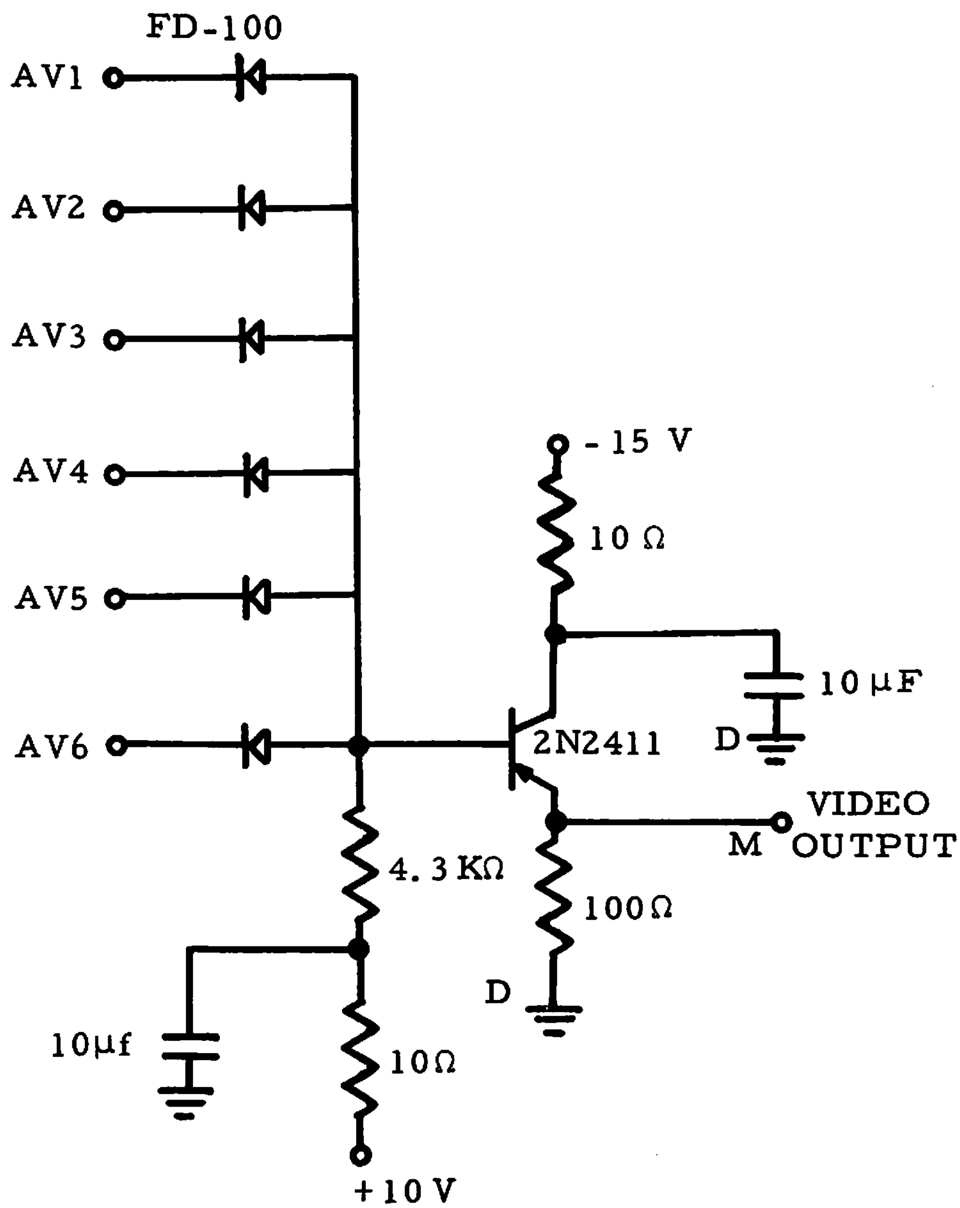

Figure 7-8. --Video synthesizer

CHAPTER 8

VIEWING TESTS OF BASIC STOP-SCAN EDGE DETECTION SYSTEM

8.1 Video Quantization Tests

Exhibit 8-1 contains photographs of television pictures with and without video amplitude quantization. The seven quantization levels were set to a logarithmic scale at the levels given in table 4-1. In the test arrangement, the video signal from the experimental system camera was quantized by the quantizer switches, and the switch outputs were fed directly to the video synthesizer for reconstruction of the video signal. The quantized pictures serve as a quality reference for pictures coded and decoded by the basic stop-scan edge detection system.

8.2 Stop-Scan Edge Coding Tests

Exhibit 8-2 contains photographs of television pictures coded and decoded by the experimental basic stop-scan edge detection system in a fixed line rate mode of operation. The indicated bandwidth reduction factors are referenced to a five bit per sample pulse code modulation coding.

EXHIBIT 8-1

VIDEO AMPLITUDE RENDITION VIEWING TESTS

Plate 1

Photo 1

Moon - no Quantization

Photo 2

Moon - 7 Level Logarithmic Quantization

PHOTO 1

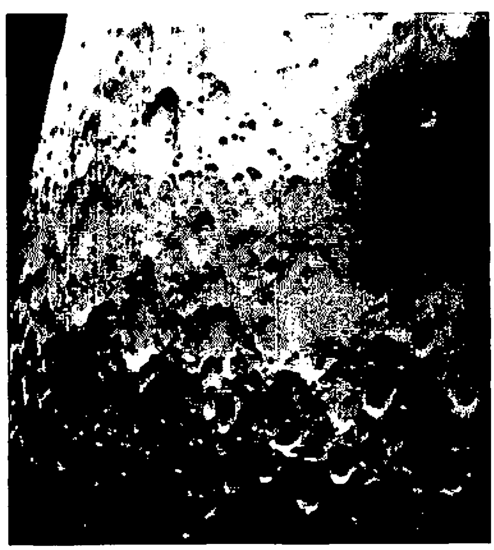

PHOTO 2

EXHIBIT 8-1

VIDEO AMPLITUDE RENDITION VIEWING TESTS

Plate 2

<u>Photo 3</u>

Olin Hall - no Quantization

<u>Photo 4</u>

Olin Hall - 7 Level Logarithmic Quantization

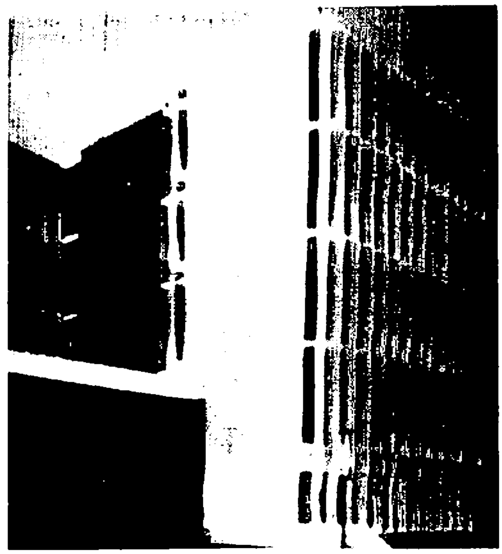

PHOTO 3

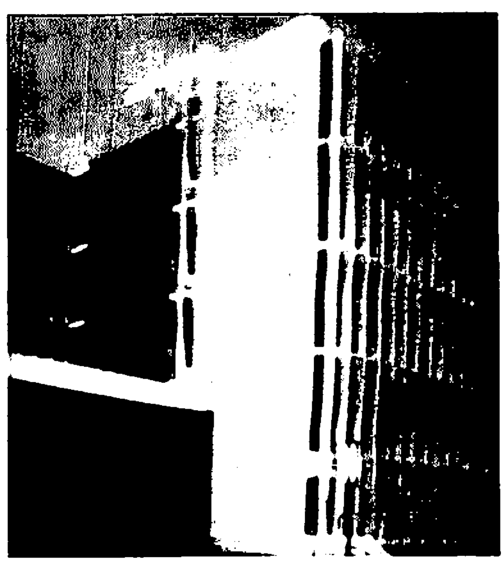

PHOTO 4

EXHIBIT 8-1

VIDEO AMPLITUDE RENDITION VIEWING TESTS

Plate 3

Photo 5

Engineering Quadrangle - no Quantization

Photo 6

Engineering Quadrangle - 7 Level Logarithmic Quantization

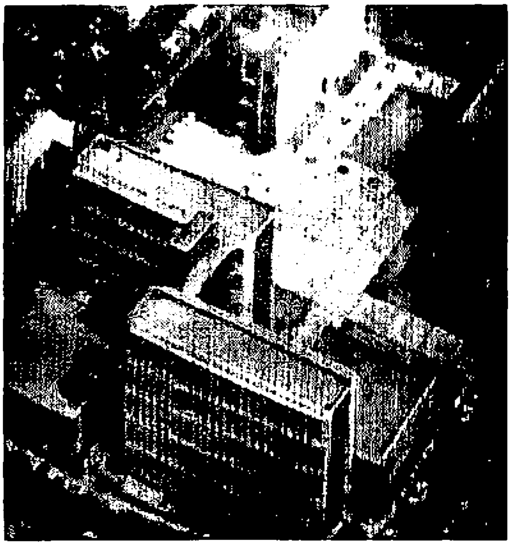

PHOTO 5

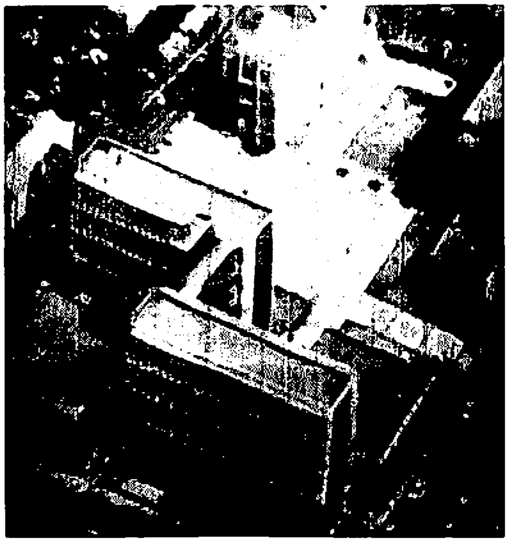

PHOTO 6

EXHIBIT 8-2

STOP-SCAN EDGE CODING VIEWING TESTS

Plate 1

Photo 1

Black and White Bar Chart - with Stop-Scan Edge Coding
Bandwidth Reduction Factor = 6.7

Photo 2

Moon - with Stop-Scan Edge Coding
Bandwidth Reduction Factor = 4.0

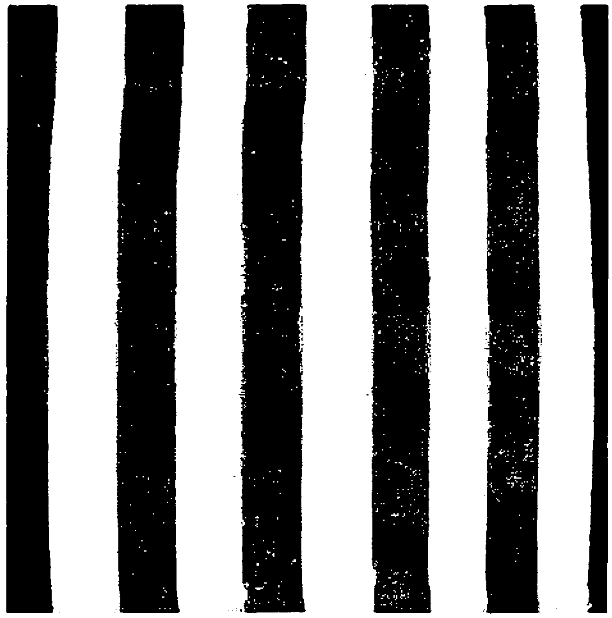

PHOTO 1

PHOTO 2

EXHIBIT 8-2

STOP-SCAN EDGE CODING VIEWING TESTS

Plate 2

Photo 3

Olin Hall - with Stop-Scan Edge Coding
Bandwidth Reduction Factor = 4.0

Photo 4

Engineering Quadrangle - with Stop-Scan Edge Coding
Bandwidth Reduction Factor = 4.0

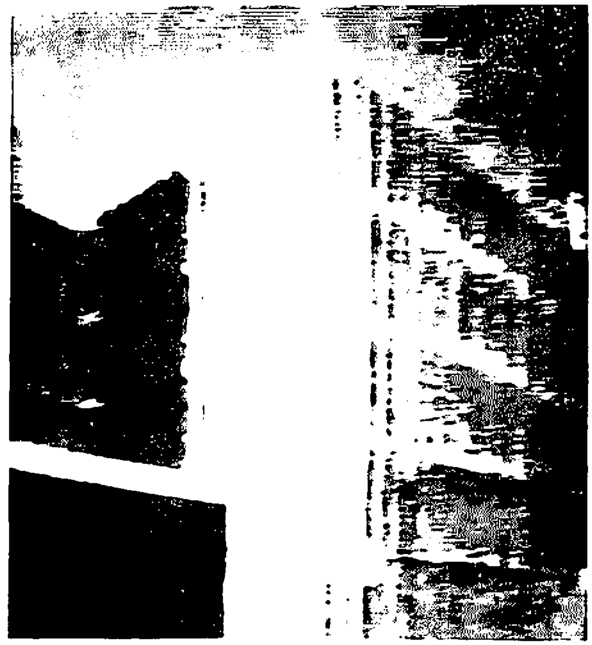

PHOTO 3

PHOTO 4

CHAPTER 9

SUMMARY

9.1 Discussion of Results

This dissertation has presented an operational description and supporting analysis of a family of television bandwidth reduction systems based upon the edge detection concept. The basic edge detection system has been fully implemented to prove its feasibility.

It has been shown that a television picture may be adequately coded and reconstructed at a reduced bandwidth from a knowledge of the positions of its brightness changes, or edges, and the visual information at the edges. Most significantly, the dissertation has established that a television bandwidth reduction may be achieved without a large size dynamic memory unit at either the coder or decoder by the use of the stop-scan video signal generation and display processes.

An analysis has indicated that the amount of television bandwidth reduction possible with edge detection coding is potentially large, and that the bound may be approached quite closely with constant word length codes. The optimum values of the edge code word length and the edge transmission rate have been derived as a function of picture detail.

The experimental portion of the dissertation project has succeeded in proving the efficacy of the edge detection and stop-scan processes by actual demonstration. Equipment has been built which digitally controls the sweep of a television monitor and camera to a high degree of accuracy and stability. Furthermore, a vidicon camera has been constructed which generates pulsed video signals upon sequential but asynchronous command. A cathode ray tube monitor which also displays pulsed video signals upon sequential asynchronous command has been built.

9.2 Extensions of Research

The research effort described by this dissertation represents a preliminary investigation into television bandwidth reduction and processing by edge detection. Further study is required in several areas.

Alternate methods of forming edges should be investigated in addition to seeking improvements in the design of the experimental edge detector. Detailed designs should be formulated for the line correlation, vector correlation, and frame difference edge detection systems. Implementation investigations will then be required for the systems.

Analysis and study should also be undertaken into techniques of processing edge information for the recognition and analysis of visual images.

9.3 Applications of Research

The television bandwidth reduction systems developed in this dissertation project have a multitude of direct and practical applications. In addition, the techniques and concepts are applicable to the processing of visual information. Examples of these applications are listed below.

9.3.1 Television Applications

The reduction of television bandwidth by stop-scan edge detection will permit a reduction in transmitted power, and hence weight, for an interplanetary spacecraft transmitting pictures to earth. By using the edge detection systems intercontinental communications satellites will be able to relay several television channels for each channel now relayed. Television bandwidth reduction will also make possible the use of less expensive ground stations for the reception of television from communications satellites because smaller diameter antennas may be utilized. The relaying of television between ground stations by cable or radio can be handled with narrower band communications equipment using the edge detection systems. Facsimile pictures and weather maps will be transmitted at a much higher rate with the systems.

9.3.2 Other Applications

The technique of stop-scan edge detection has many potential applications for the processing of visual information. For example, blood samples may be analyzed by microscopically scanning stained slides with a stop-scan camera. An edge will be generated whenever the scan beam moves from a stained to an unstained section of the slide. The amplitude and position of the edges may then be processed to give the size, shape, and count of the stained sections. Similar techniques may be applied to the analysis of impurities in a semiconductor material.

Many space applications exist for automatically detecting and recognizing unknown space vehicles. The shape and size of an unknown satellite may be found, for example, by scanning the image of the satellite with a stop-scan camera, and processing the edges.

Finally, the concept of stop-scan information gathering process, and the methods developed for its implementation may be utilized for sequential target detection systems.

GLOSSARY

Y_i = brightness of ith element of a picture

Z = edge run length for natural edge coding

Z_M = edge run length for pseudo-edge coding

X_F = number of edges per frame

X_L = number of edges per line

W = number of edge code bits per element

p = probability that a natural edge occurs at ith element

q = $1 - p$

M = maximum edge run length

A = number of video amplitude bits per edge

G = number of position bits per edge

Q = number of correlation, vector slope, and vector length bits per edge

G_R = number of position bits per edge in reference frame channel

G_D = number of position bits per edge in difference frame channel

Q_R = number of correlation, vector slope, and vector length bits per edge

Q_D = number of correlation, vector slope, and vector length bits per edge

$N_{D,F}$ = number of elements per frame

$N_{D,L}$ = number of elements per line

$N_{E,S}$ = number of edges transmitted per second

$N_{E,F}$ = number of edges transmitted per frame

$N_{E,L}$ = number of edges transmitted per line

$N_{B,E}$ = number of code bits per edge

$N_{F,Q}$ = number of frames per sequence

$N_{E,F,R}$ = number of edges transmitted per frame in reference frame channel

$N_{E,F,D}$ = number of edges transmitted per frame in difference frame channel

$N_{E,L,R}$ = number of edges transmitted per line in reference frame channel

$N_{E,L,D}$ = number of edges transmitted per line in difference frame channel

$N_{B,E,R}$ = number of code bits per edge in reference frame channel

$N_{B,E,D}$ = number of code bits per edge in difference frame channel

$N_{B,D}$ = number of video amplitude bits per element with conventional coding

R_B = transmission bit rate

APPENDIX I

SURVEY AND ANALYSIS OF TELEVISION BANDWIDTH REDUCTION SYSTEMS

Literally dozens of different methods of television bandwidth reduction have been proposed. However, in terms of basic concepts or principals the many methods may be classified into a few categories. Representative systems of each category are listed in table I-1.

These systems have been analyzed in an effort to select the ones which offer the greatest promise in terms of bandwidth reduction, picture fidelity, and implementation feasibility. The bandwidth reduction possible with the systems, and a summary of the attendent disadvantages of the systems is listed in table I-2.

TABLE I-1

TELEVISION BANDWIDTH REDUCTION SYSTEMS

1. Basic Methods
   - Reduced Horizontal Resolution
   - Reduced Vertical Resolution
   - Reduced Frame Rate
   - Reduced Blanking Time Ratio

2. Picture Interlace
   - Line Interlace
   - Dot Interlace

3. Spectrum Interlace
   - Frequency Interlace

4. Nonstatistical Quantization
   - Split Band Quantization
   - Deltamodulation
   - Pseudorandom Noise Coding

5. Interframe Processing
   - Electronic Processing
   - Optical Processing

6. Interframe Redundancy Removal
   - Variable Velocity Scanning
   - Edge Detection
   - Line Correlation Edge Detection
   - Vector Correlation Edge Detection
   - Synthetic Highs
   - Element Prediction
   - Line Contour Interpolation
   - Area Coding
   - Pattern Recognition

7. Intraframe Redundancy Removal
   - Frame Difference Coding
   - Frame Difference Edge Detection
   - Frame Difference Dot Interlace
   - Frame Run Coding

TABLE I-2

INVESTIGATION SUMMARY OF TELEVISION BANDWIDTH REDUCTION SYSTEMS

Techniques	Major Disadvantages	Bandwidth Reduction
Basic Methods	1. Picture quality is directly degraded	2-5
Line Interlace	1. High order line interlace ratios tend to create line crawling effects and image breakup	2-4
Dot Interlace	1. Some dot patterning and line crawling effects even with the use of pseudo-random scanning sequences 2. Image breakup proportional to bandwidth reduction factor	2-16
Split Band Quantization	1. Some picture degradation	2
Deltamodulation	1. High frequency brightness changes cannot be followed faithfully	2-4

Techniques	Major Disadvantages	Bandwidth Reduction
Pseudo-Random Noise Coding	1. Some picture degradation	2
Frequency Interlace	1. Inherent line crawling effect	2
Variable Velocity Scanning	1. Brightness resolution degradation 2. Incorrectable spatial distortion 3. Signal-to-noise ratio 30 db. higher than conventional system	5-7
Edge Detection	1. Edge position transmission errors produce element offset errors in a scan line	4-6
Line Correlation Edge Detection	1. Edge position transmission errors	6-7
Vector Correlation Edge Detection	1. Edge position transmission errors	7-10
Synthetic Highs	1. Edge position transmission errors	4-6
Element Prediction	1. Errors propagate	2-4
Contour Interpolation	1. Cannot follow abruptly changing picture contours	2-4

Techniques	Major Disadvantages	Bandwidth Reduction
Pattern Recognition	1. Not practical, systems require a large amount of computation to recognize simplest patterns	–
Area Coding	1. Difficult to implement 2. Area registration errors	2-5
Electronic Processing	1. Picture quality is directly degraded	2-4
Optical Processing	1. Picture quality is directly degraded	2-5
Frame Difference	1. Frame differencing errors	5
Frame Difference Edge Detection	1. Frame differencing errors 2. Edge position transmission errors	10-20
Frame Difference Dot Interlace	1. Dot interlace of frame difference signal causes non-correctable errors which affect picture quality adversely	2-16
Frame Run Coding	1. Jerkiness between frames 2. Reduced spatial resolution of moving objects	8-10

APPENDIX II

ANALOG TRANSMISSION OF EDGES

It is possible to transmit edges in an analog modulation communication system by letting the amplitude and position of an edge be proportional to the amplitude of the transmitted carrier. The video amplitude of an edge may be quantized in as few as 6-7 gray scale levels. However, an edge position requires about 16-32 levels to achieve a large bandwidth reduction. Because of the greater number of edge position quantization levels, and the greater subjective penalty of edge position errors, the communication signal-to-noise ratio (SNR) requirements are set by the transmission of edge position.

Let the maximum amplitude B of the communications carrier be quantized into M (the maximum edge run length) quantization levels. Assuming white Gaussian noise with mean zero the probability of an edge position decoding error for the jth quantization level is

$$P_e(j) = \int_{\frac{B}{2M}}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{W^2}{2\sigma^2}} dW \quad \text{for} \quad j \neq 0, \; j \neq M$$

and

$$P_e(j) = \int_{\frac{B}{2M}}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{W^2}{2\sigma^2}} dW \quad \text{for} \quad j = 0, \quad j = M$$

Assuming the occurrence of an error in each level to be equally likely, the average probability of error is

$$P_e = 2 \frac{M-1}{M} \int_{\frac{B}{2M\sigma}}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{W^2}{2}} dW$$

The ratio B/σ is the peak signal voltage to rms noise voltage ratio. In commercial quality television this ratio is about 30 db. With a 30 db SNR, and with M set at 6, on the average one edge in every 146 will be in error. Referring to equation 4.13 for M = 6, and the probability of an edge occurrence p = 0.1, the average edge run length M is slightly greater than 4.

For M = 6, the bandwidth reduction factor of the analog transmission edge detection system compared to an analog television system is

$$BWR = \frac{\overline{Z}_M}{2}$$

Thus, even with an edge error rate greater than one edge error every line, the bandwidth reduction factor is only 2. As shown in Chapter 5, a bandwidth reduction factor of about 5-6 can be realized with a much lower edge position error rate with digital edge transmission.

APPENDIX III

EDGE DETECTION TECHNIQUE

An edge occurs if the amplitude difference between adjacent elements along a line exceeds a specified threshold value. For a bilevel system this threshold level is one-half the expected peak video amplitude. The threshold level for a multilevel system is equal to the lowest quantization level for video amplitude coding.

Classification of Edges

Figure III-1 illustrates a classification of edges for a multilevel system for the nine possible arrangements of the relative amplitudes of three adjacent elements. Julesz [32] in his investigation of edge detection did not consider the class I arrangements to be edges. While such a definition reduces bandwidth to a slightly greater degree, the implementation of the edge detector is much more complex.

Edge Generation

In a bilevel system it is not actually necessary to form the amplitude difference between adjacent elements to determine if an edge exists. Instead, it is only necessary to detect whether the threshold is exceeded in one element of a pair of adjacent elements,

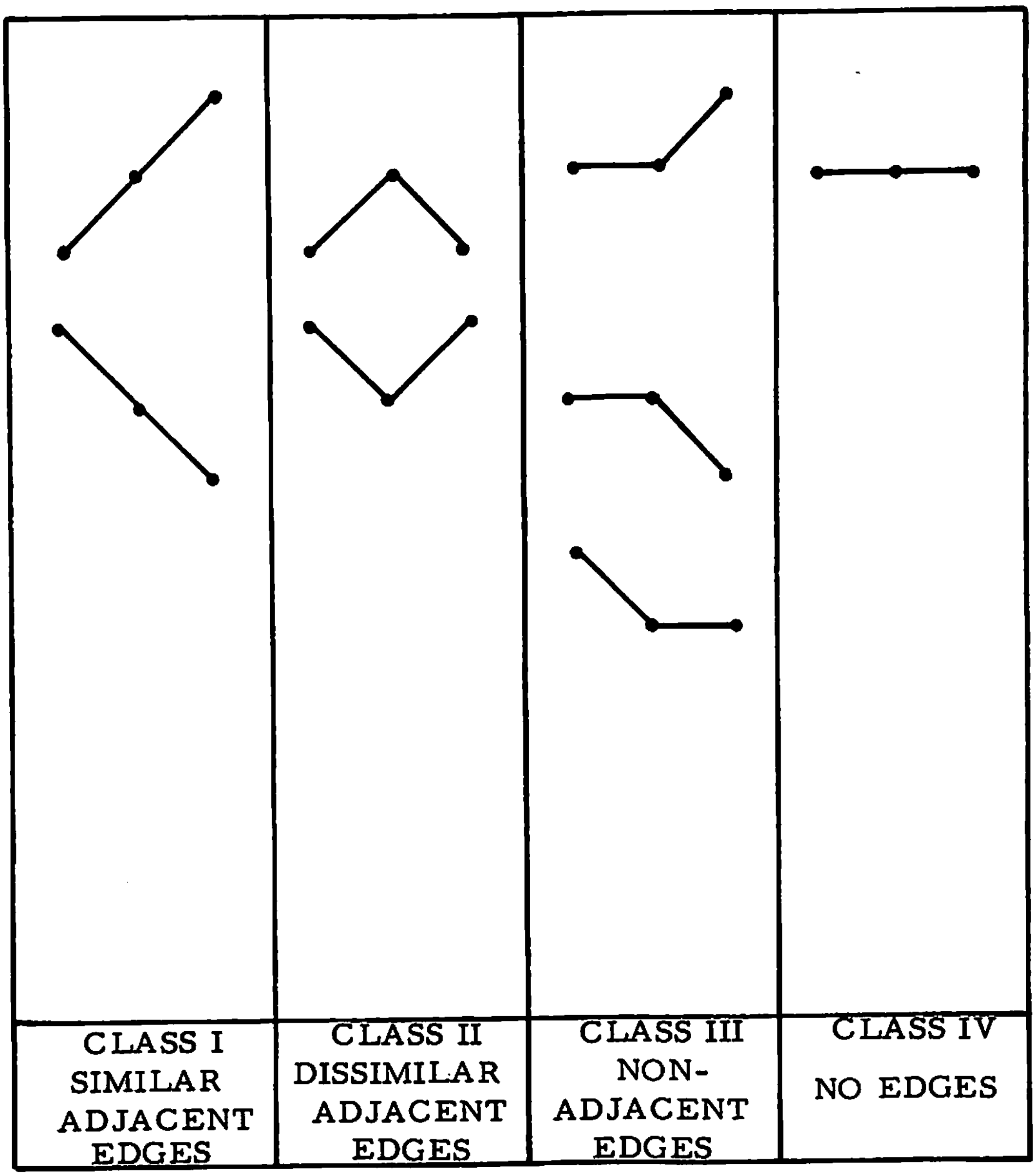

Figure III-1. --Classification of edges, brightness versus element position and not exceeded in the other element. With a multilevel system essentially the same procedure may be followed. The lowest amplitude quantization levels passed by each of two adjacent pulses are compared; if the levels are not identical, an edge exists. This technique introduces edge detection errors due to the quantization of video amplitudes for storage.

Quantization errors may be eliminated by storing the amplitude of each video pulse in analog form, and comparing its amplitude to the next element scanned. Unfortunately, asynchronous analog storage devices are difficult to implement at video signal frequencies. This implementation problem may be avoided by using a simple passive delay line with a delay of one element period under the restriction that the second edge of a pair of spatially adjacent edges will not be detected. The reason for this restriction is that, with the stop-scan process, the time delay between the scanning of elements may vary from one to several elements, while the delay of the delay line is fixed. Thus, when scanning is resumed after an edge is detected, the amplitude of the last element scanned will be lost.

Non-Adjacent Edge Generation

From equation 4. 5, the probability that two edges will be adjacent is the probability that the edge run length is one.

$$P_r(Z_M = 1) = p$$

The measured picture statistics of chapter 6 place p at a value of about 0.1 or less. Thus, the probability of adjacent edges is 0.1 or less.

Missing an adjacent edge creates errors in a displayed picture if the edges are of class I or class II as shown in figure III-2. The error exhibited in cases (a), (c), (d), and (f) only lasts for one element period. The error in cases (b) and (e) persists until another natural edge or a pseudo edge is detected.

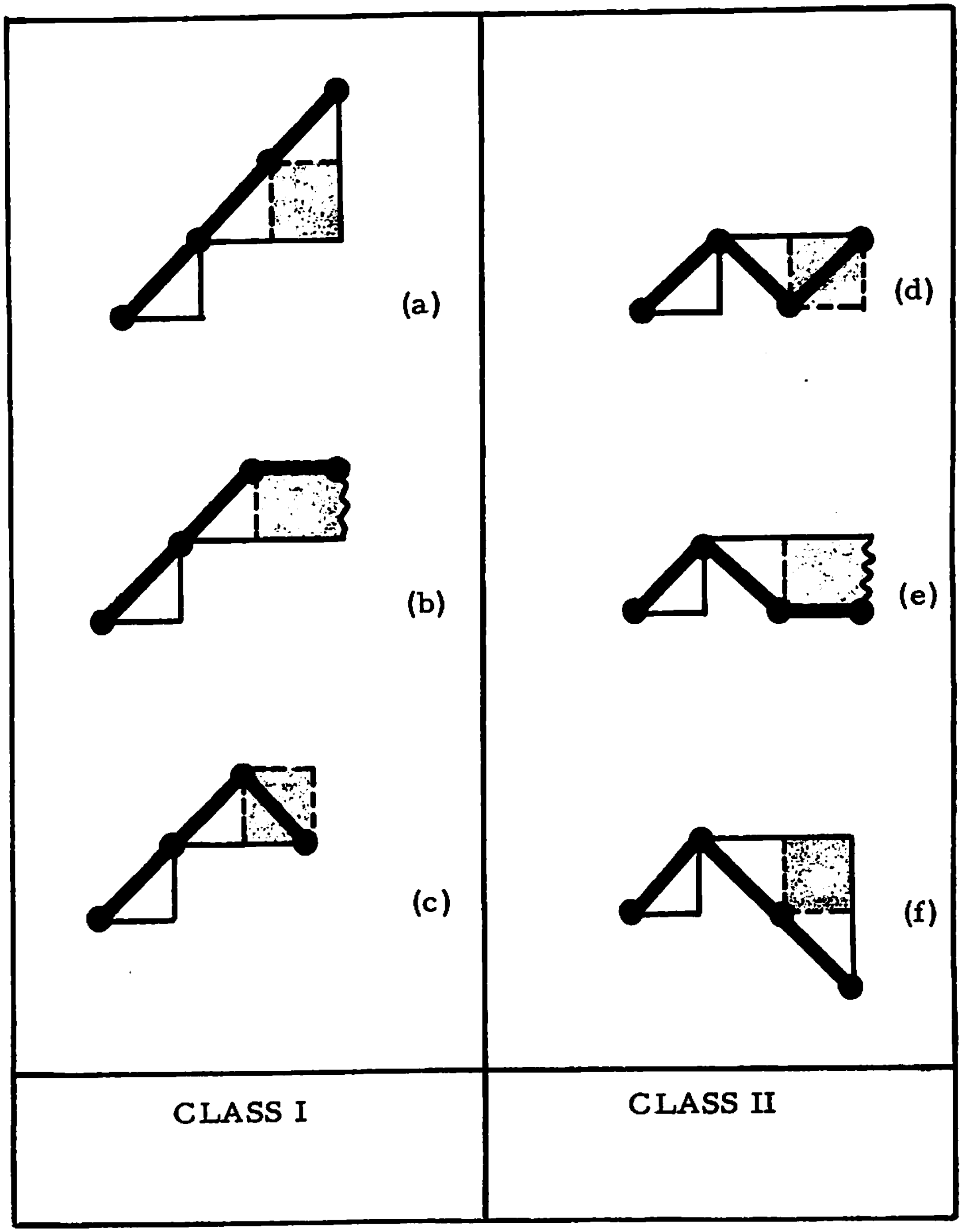

Figure III-2. --Classification of edge detection errors, brightness versus element position

APPENDIX IV

EXPERIMENTAL SYSTEM LOGIC EQUATIONS

The logic equations for the experimental basic stop-scan edge detection system are presented on the following pages. The nomenclature for the equations is listed below. Descriptions of the logic devices are given in: "Digital Equipment Corporation System Modules Catalog C-100".

LOGIC NOMENCLATURE

<u>Flip-Flop</u>

Set to mark:	MI <u>XXXX</u>
Reset to zero:	XI <u>XXXX</u>
Direct clear:	DC <u>XXXX</u>
Direct set:	DS <u>XXXX</u>
Input pulse complement:	PI <u>XXXX</u>
Mark output:	MO <u>XXXX</u>
Zero output:	ZO <u>XXXX</u>
Output pulse complement:	PO <u>XXXX</u>

<u>Logic Gate</u>

Output:	G <u>XXXX</u>
Inverted output:	IG <u>XXXX</u>

<u>Clock Pulse</u>

Output:	CP <u>XXXX</u>
Delayed output:	CP <u>XXXX</u> D

<u>Reference Voltage</u>

V <u>XXXX</u>

<u>Amplified Voltage</u>

AV <u>XXXX</u>

EXPERIMENTAL SYSTEM LOGIC EQUATIONS

Transmitter

Timing Generator

CPC = Clock Pulse

PIT1 = CPC
PIT2 = (POT1)(MOT1)
PIT3 = (POT2)(MOT2)
PIT4 = (POT3)(MOT3)
PIT5 = (POT4)(MOT4)

DST = CPS
DCX = CPS

CPE = CPC
CPO = (CPC)(MOT1)(MOT2)
CPR = (CPC)(MOT1)(MOT2)(MOT3)(MOT4)(MOT5)

GPA = (MOT3)(MOT4)(MOT5)
CPA = (CPO)(GPA)
CPB = (CPO)(IGPA)
GPS = CPS

Camera Control

Horizontal Counter

PIH1 = CSND1
PIH2 = (POH1)(MOH1)
PIH3 = (POH2)(MOH2)
PIH4 = (POH3)(MOH3)
PIH5 = (POH4)(MOH4)
PIH6 = (POH5)(MOH5)
PIH7 = (POH6)(MOH6)
PIH8 = (POH7)(MOH7)
PIH9 = (POH8)(MOH8)

Vertical Counter

PIV1 = (GLE)(IGV383)
PIV2 = (POV1)(MOV1)
PIV3 = (POV2)(MOV2)
PIV4 = (POV3)(MOV3)
PIV5 = (POV4)(MOV4)
PIV6 = (POV5)(MOV5)
PIV7 = (POV6)(MOV6)
PIV8 = (POV7)(MOV7)
PIV9 = (POV8)(MOV8)

Framing Counter

PIN1 = CPR
PIN2 = (PON1)(MON1)
PIN3 = (PON2)(MON2)
PIN4 = (PON3)(MON3)
PIN5 = (PON4)(MON4)

Scan Control Logic

GN31 = (MON5)(MON4)(MON3)(MON2)(MON1)
GN30 = (MON5)(MON4)(MON3)(MON2)(ZON1)
GH371 = (MOH9)(ZOH8)(MOH7)(MOH6)(MOH5)(ZOH4)(ZOH3)(MOH2)(MOH1)
GV383 = (MOV9)(ZOV8)(MOV7)(MOV6)(MOV5)(MOV4)(MOV3)(MOV2)(MOV1)

GLE = (CPR)(GN30)
GNE = (CPR)(GN31)
GSE = (CSND1)(GH371)
GFE = (GLE)(GV383)
GSN = (ZOS1)(ZOS2)

DCH = GPS + GLE
DCV = GPS + GFE
DCN = GPS + GNE

MIS1 = GRE
ZIS1 = CPR (Scan)
MIS2 = GLE + GSE
ZIS2 = GNE + GPS (Active Element)

CSND1	=	(CPE)(GSN) + (CPR)(ZOS2)	
CSND2	=	(CPE)(GSN) + (CPR)(ZOS2) + GNE	Delayed
CSND3	=	(CPE)(GSN) + GNE	Delayed
CSND4	=	(CPE)(GSN) + GNE	Delayed

<u>Edge Detector</u>

Quantizer Switches

GD1 = 1 VS > VE1
GD2 = 1 VS < VE2

Edge Gate

GRE = (CSND3)(GD1 + GD2)

<u>Video Amplitude Coder</u>

Quantizer Switches

GC1 = 1 VS < VA1
GC2 = 1 VS < VA2
GC3 = 1 VS < VA3
GC4 = 1 VS < VA4
GC5 = 1 VS < VA5
GC6 = 1 VS < VA6

<u>Video Amplitude Bits Storage</u>

MIB1 = (CSND4)(GC4) + GLE
ZIB1 = (CSND4)(IGC4)
MIB2 = (CSND4)(GC2)(IGC5) + GLE
ZIB2 = (CSND4)(IGC2 + GC5)
MIB3 = (CSND4)((GC1)(IGC3) + GC6) + GLE
ZIB3 = (CSND4)(IGC6)(IGC1 + GC3)

Output Register

MIX1 = (CPA)(MOB1) + (CPB)(ZOX2)
ZIX1 = (CPA)(ZOB1) + (CPB)(MOX2)
MIX2 = (CPA)(MOB2) + (CPB)(ZOX3)
ZIX2 = (CPA)(ZOB2) + (CPB)(MOX3)
MIX3 = (CPA)(MOB3) + (CPB)(ZOX4)
ZIX3 = (CPA)(ZOB3) + (CPB)(MOX4)
MIX4 = (CPA)(MOH1) + (CPB)(ZOX5)
ZIX4 = (CPA)(ZOH1) + (CPB)(MOX5)
MIX5 = (CPA)(MOH2) + (CPB)(ZOX6)
ZIX5 = (CPA)(ZOH2) + (CPB)(MOX6)
MIX6 = (CPA)(MOH3) + (CPB)(ZOX7)
ZIX6 = (CPA)(ZOH3) + (CPB)(MOX7)
MIX7 = (CPA)(MOH4) + (CPB)(ZOX8)
ZIX7 = (CPA)(ZOH4) + (CPB)(MOX8)
MIX8 = (CPA)(MOH5)
ZIX8 = (CPA)(ZOH5)

Receiver

Timing Generator

CPC = Clock Pulse

PIT1 = CPC
PIT2 = (POT1)(MOT1)
PIT3 = (POT2)(MOT2)
PIT4 = (POT3)(MOT3)
PIT5 = (POT4)(MOT4)

DST = CRS

CPE = CPC
CPO = (CPC)(MOT1)(MOT2)
CPR = (CPC)(MOT1)(MOT2)(MOT3)(MOT4)(MOT5)
GRS = CRS

Monitor Control

Horizontal Counter

PIH1 = CSND1
PIH2 = (POH1)(MOH1)
PIH3 = (POH2)(MOH2)
PIH4 = (POH3)(MOH3)
PIH5 = (POH4)(MOH4)
PIH6 = (POH5)(MOH5)
PIH7 = (POH6)(MOH6)
PIH8 = (POH7)(MOH7)
PIH9 = (POH8)(MOH8)

Vertical Counter

PIV1 = (GLE)(IGV383)
PIV2 = (POV1)(MOV1)
PIV3 = (POV2)(MOV2)
PIV4 = (POV3)(MOV3)
PIV5 = (POV4)(MOV4)
PIV6 = (POV5)(MOV5)
PIV7 = (POV6)(MOV6)
PIV8 = (POV7)(MOV7)
PIV9 = (POV8)(MOV8)

Framing Counter

PIN1 = CPR
PIN2 = (PON1)(MON1)
PIN3 = (PON2)(MON2)
PIN4 = (PON3)(MON3)
PIN5 = (PON4)(MON4)

Scan Control Logic

GN30 = (MON5)(MON4)(MON3)(MON2)(ZON1)
GH371 = (MOH9)(ZOH8)(MOH7)(MOH6)(MOH5)(ZOH4)(ZOH3)(MOH2)(MOH1)
GV383 = (MOV9)(ZOV8)(MOV7)(MOV6)(MOV5)(MOV4)(MOV3)(MOV2)(MOV1)

GLE = (CPR)(GN30)
GNE = (CPR)(GTS)
GSE = (CSND1)(GH371)
GFE = (GLE)(GV383)
GSN = (ZOS1)(ZOS2)
GEE = (GCC)(CSND3)

DCH = GRS + GLE
DCV = GRS + GFE
DCN = GRS + GNE

GTS = (MOL1)(MOL2)(MOL3)

MIS1 =	GEE	
ZIS1 =	CPR	(Scan)
MIS2 =	GLE + GSE	
ZIS2 =	GNE + GRS	(Active Element)

CSND1 =	(CPE)(GSN) + (CPR)(ZOS2)	
CSND2 =	(CPE)(GSN) + (CPR)(ZOS2)	Delayed
CSND3 =	(CPE)(GSN) + GNE	Delayed

<u>Input Register</u>

MIF8 = (IINPUT)(CPO)
ZIF8 = (INPUT)(CPO)
MIF7 = (ZOF8)(CPO)
ZIF7 = (MOF8)(CPO)
MIF6 = (ZOF7)(CPO)
ZIF6 = (MOF7)(CPO)
MIF5 = (ZOF6)(CPO)
ZIF5 = (MOF6)(CPO)
MIF4 = (ZOF5)(CPO)
ZIF4 = (MOF5)(CPO)
MIF3 = (ZOF4)(CPO)
ZIF3 = (MOF4)(CPO)
MIF2 = (ZOF3)(CPO)
ZIF2 = (MOF3)(CPO)
MIF1 = (ZOF2)(CPO)
ZIF1 = (MOF2)(CPO)

Storage Register

Position Bits

MID5 = (ZOF8)(CPR)
ZID5 = (MOF8)(CPR)
MID4 = (ZOF7)(CPR)
ZID4 = (MOF7)(CPR)
MID3 = (ZOF6)(CPR)
ZID3 = (MOF6)(CPR)
MID2 = (ZOF5)(CPR)
ZID2 = (MOF5)(CPR)
MID1 = (ZOF4)(CPR)
ZID1 = (MOF4)(CPR)

Amplitude Bits

MIA3 = (ZOF3)(CPR)	MIL3 = (ZOA3)(CPR)
ZIA3 = (MOF3)(CPR)	ZIL3 = (MOA3)(CPR)
MIA2 = (ZOF2)(CPR)	MIL2 = (ZOA2)(CPR)
ZIA2 = (MOF2)(CPR)	ZIL2 = (MOA2)(CPR)
MIA1 = (ZOF1)(CPR)	MIL1 = (ZOA1)(CPR)
ZIA1 = (MOF1)(CPR)	ZIL1 = (MOA1)(CPR)

Edge Position Comparator

GC5 = (MOD5)(MOH5) + (ZOD5)(ZOH5)
GC4 = (MOD4)(MOH4) + (ZOD4)(ZOH4)
GC3 = (MOD3)(MOH3) + (ZOD3)(ZOH3)
GC2 = (MOD2)(MOH2) + (ZOD2)(ZOH2)
GC1 = (MOD1)(MOH1) + (ZOD1)(ZOH1)

GCC = (GC1)(GC2)(GC3)(GC4)(GC5)

Video Amplitude Decoder

GV6 = (MOL1)(ZOL2)(MOL3)
GV5 = (MOL1)(ZOL2)(ZOL3)
GV4 = (MOL1)(MOL2)(ZOL3)
GV3 = (ZOL1)(MOL2)(ZOL3)
GV2 = (ZOL1)(MOL2)(MOL3)
GV1 = (ZOL1)(ZOL2)(MOL3)

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