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Summary

Visual textures may be described completely by their spatial frequency components. For one-dimensional textures whose luminance varies only along the X-axis of the display, the descriptive elements are gratings that have sinusoidal modulations of luminance. Although any arbitrary one-dimensional "blurred" texture may require a very large number of sinusoidal components for its complete physical description, only four components are needed to create a texture that appears the same to the human observer. Thus, the human visual system does not act like a spectral analyser, but rather appears to process spatial frequency information by filtering operations similar to that performed in color vision, at least for one-dimensional texture patterns. In the more general case, textures will have luminance distributions varying in two dimensions (i.e., both X and Y). To test for the minimum number of spatial frequencies required to simulate two-dimensional texture patterns, we are building a new graphics display. The apparatus will permit on-line control of the amplitude (contrast) of the (X,Y) frequency (Fourier) components that make up the texture displayed. Thus, the observer will be able to generate a texture that appears identical to another texture having a different and more complex spatial frequency content. Of interest is the minimum number of spatial frequency components necessary to simulate all two-dimensional textures. If we find, as we did for one-dimensional textures, that only four spatial frequency components are necessary, then we may proceed to design a scheme for transmitting visual information about textures that offers a considerable saving in channel capacity.

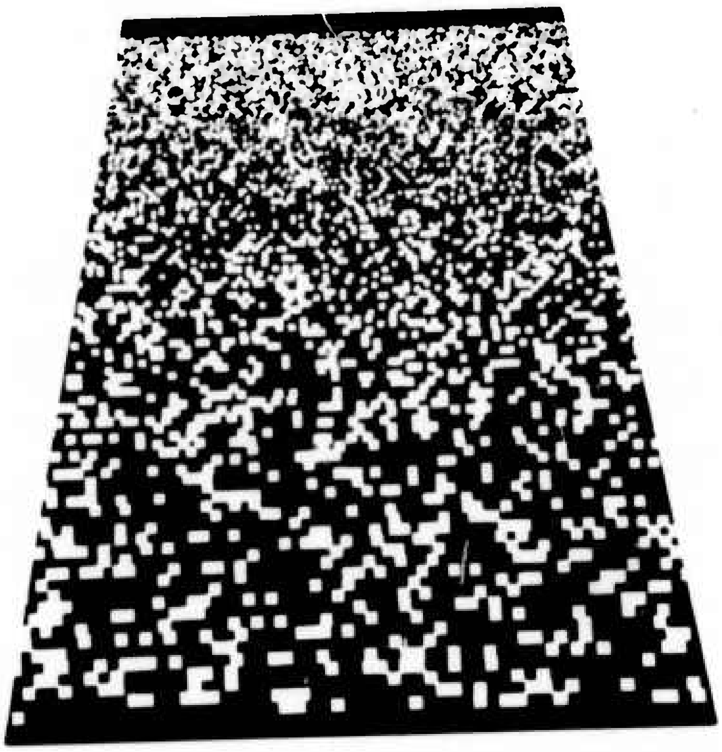

Figure 1

A computer-generated texture gradient. The grain size increases by 1.3 percent from one line to the next lower row. (Courtesy of A. Polit).

Contents

Experiments in Texture Perception

I. Introduction

Texture, like color, is one of the primary properties of an object (Metzger, 1926; Koffka, 1935). Yet our knowledge of the texture recognition process of the human observer is meagre. Previous studies of texture may be crudely divided into three categories:

1.) texture gradients as shown in Fig. 1 and their roles in slant and depth perception (Gibson, 1950; Gruber and Clark, 1956; Wohlwill, 1962; Flock and Moscatelli, 1964; Kraft and Winnick, 1967);

2.) texture discrimination and its relation to the statistical properties of the display as illustrated in Fig. 5 (Jones and Higgins, 1947; McBride and Reed, 1952; Green et al, 1959; Stultz and Zweig, 1959; Julesz, 1962, 1965; Pickett, 1962, 1964, 1967) and

3.) the search for continua suitable for an objective definition of "texture" (Jones and Higgins, 1945; Rosenfeld, 1967; Pickett, 1968; Minsky and Papert, 1969; Julesz, 1971).

Although clearly relevant to these previous studies, our primary approach to texture perception is entirely new and falls into still another category. The novelty of the new approach is that it is concerned only with describing textures that appear equivalent to the human observer, rather than trying to specify the physical characteristic that will differentiate between all textures. The

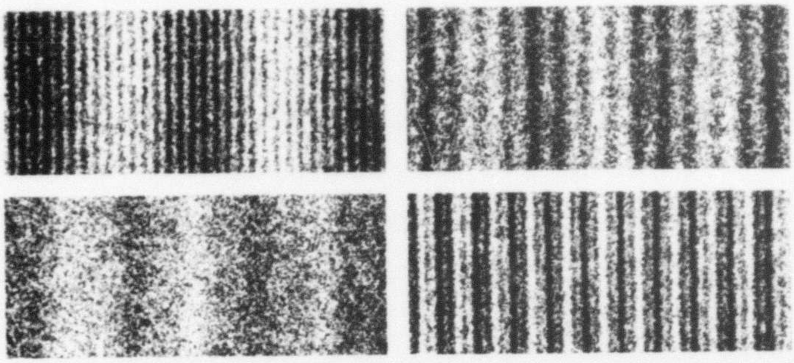

Figure 2

Four examples of one-dimensional textures composed of only a few sinusoidal components. As the number of components increases, the textures approach the middle texture of Fig. 3.

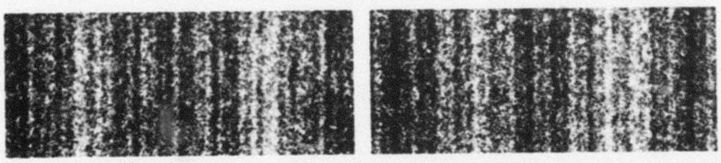

Figure 3

The pattern at the left contains noise restricted to the range 0.2 -20 c/deg when viewed at 50 cm. The texture on the right, which is considered a texture metamer, contains only three frequency components, 0.53, 2.4 and 6.5 c/deg.

attempt to describe equivalent textures therefore is quite analogous to the development of color science where the primary concern was to identify spectral compositions that would appear equivalent to the human observer. Such energy distributions that were physically different but appeared equivalent were called metamers. Our approach to texture perception is to describe such metamers.

The first step in describing color equivalences was the recognition of the dimension of wavelength along which all spectral compositions could be physically represented. Texture may also be described in exactly the same way except the relevant dimension is now spatial frequency. Thus, if at the onset only one-dimensional textures are considered such as those shown in Fig. 2, then Fourier's theorem states that any such texture may be adequately described by the magnitude of its sinusoidal components. These components are of course merely sine-wave gratings which when added together in suitable proportions will physically recreate the one-dimensional texture pattern. Thus, the dimension of spatial frequency is used to describe all possible one-dimensional textures in exactly the same manner that chromatic wavelength is used to describe all possible colors.

In color it was discovered during the last century that only three suitably chosen wavelengths were needed to generate equivalences to all possible physically realizable colors (Maxwell, 1855; Wright, 1928; Guild, 1931). This property of color equivalences is imposed by the fact that human color perception is based upon the energy passed through only three independent filters each having a different wavelength characteristic (Stiles and Burch, 1959;

Brown and Wald, 1964; Marks, Dobelle and MacNichol, 1964). Until shown to be otherwise, it is also possible that texture perception could follow a similar principle: namely that all one-dimensional textures might be suitably matched by only a small number of suitably chosen sine-wave gratings put together in the right proportions. This research is a test of this notion.

II. One-Dimensional Textures

Textures similar to those in Figs. 2 and 3 were generated on a PDP 11/20 computer in conjunction with a Kratos display scope (the actual display was not grainy as in the present illustrations). From previous experiments (Richards and Polit, 1974), we had determined that four suitably chosen spatial frequencies might match all one-dimensional textures. Following this earlier paradigm, we chose 0.9, 2.3, 5.1 and 8.7 c/deg as our primaries for matching all sinusoidal patterns. Rather than attempting to match all possible patterns in the texture space, an additivity assumption was made: that any pattern may be described by the linear superposition of its Fourier components. Although this assumption regarding the behavior of the visual system is known to be false, particularly at high contrasts (Davidson, 1968; Cornsweet, 1970), the approximation is good at low contrasts. With this approximation it is then necessary only to speci y an equivalence between each pure sine-wave pattern and the chosen primaries in order to specify matches to all possible textures. The procedure is thus directly analogous to that used to specify color matches in colorimetry (Wyszecki and Stiles, 1967). And, like colorimetry one of the primaries will always be added as a "desaturant" to the test frequency, with the combination to be matched by the remaining two primaries. When a primary is added as a desaturant to the test frequency, the primary will assume negative values.

The sine-wave frequency spectrum was then sampled from 0.2 to 27 c/deg with the contrast of the test frequency held fixed at 0.5. Variable amounts of contrast of one of the four primaries

(0.9, 2.3, 5.1 or 8.7 c/deg) were then added to the chosen test frequency. The test frequency together with its (1 or 2) primary desaturant made up one pattern. The second pattern consisted of combinations of the remaining primaries which also were mixed together in variable amounts of contrasts. These two patterns appeared aide by side on a Kratos display, and the obaerver could control the amount of contraat of each primary. The task of the observer was therefore to adjust the contraat of the primaries (and desaturant) to make a texture match between the two fields.

In all cases a satisfactory texture match could be found. Thus, although the spatial frequency spectrum for both patterns was unequal, the textures appeared to have the same quality to the observer. The reaulta are similar to those reported earlier using a more primitive method (Richarda and Polit, 1974). Thus we may conclude that only four apatial frequencies are required to match any one dimensional texture.

III. Two-Dimensional Textures

Although a considerable amount of information about texture perception may be obtained using one-dimensional patterns, any complete description of texture analysis by the human observer must include two dimensional textures such as those illustrated in Figure 4. In order to generate such patterns and have on-line control of their spatial frequency components, we have designed and are building a special graphics display. This display will allow us to generate 400 x 400 point patterns consisting of complex (computer-generated) sinusoidal modulations of luminance that may be altered every 20 msec.

More specifically, the special visual display under construction consists of 9 subsystems as follows:

1. Monitors: Conrac SNA 17/C (2)
   Monochrome television monitors
2. Operator Controls: Two channels, each with independent control of three sinusoidal or other component amplitudes and the a(x)*a(y) product term. Control boxes are on extension cables for convenience and flexibility of location.
   A six-channel A/D converter digitizes the control settings for input to the computer.
3. Function Table Computer: A dedicated PDP 11/10 Minicomputer is used to monitor the operator controls and calculate a(u) and b(u) function tables in accordance with the operator control settings,

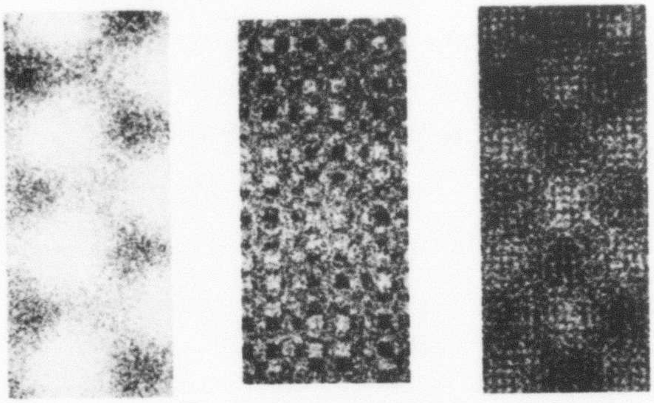

Figure 4

Examples of two-dimensional texture patterns.

where:

$$a(u) = \sum_{i=1}^{3} A_i \sin(2\pi f_i u + \phi_i)$$

$$b(u) = \sum_{i=1}^{3} B_i \sin(2\pi f_i u + \phi_i)$$

4. Video Function Generators: Two identical custom designed video generators are provided to store the computed function tables and generate a video luminance signal of the form:

$$L_A(X,Y) = 1 + a(x) + a(y) + K_A a(x)\, a(y)$$

$$L_B(X,Y) = 1 + b(x) + b(y) + K_B b(x)\, b(y)$$

Provision is made for adding an external video signal.

5. Scan Generator: A custom designed digital scan generator will generate raster coordinates, synchronizing signals and control signals.

6. Video Refresh System: A custom-designed video refresh system is provided to allow an arbitrary two-dimensional pattern to be added to the texture display. The refresh system employs a standard core memory of 32,768 thirty-six bit words and can store 196,608 picture elements (pixels) with 6 bit (64 level) gray scale.

6. Video Refresh System (contd.):

The EMM Micromemory 3000 series has been used for the core memory. Four 3000DD (16K x 18 bit) cards are mounted in a 5 1/4" high chassis together with a control and video output card, power supply and cooling fans.

The control card curcuit provides an alternate mode of operation in which four 108 x 108 checkerboard patterns can be stored and refreshed. The PDP-11/10 will have control of mode selection and can select which of the four patterns is to be displayed.

If in the future, the video refresh capability should be no longer needed, the core memory can be easily converted on site to a general purpose RAM. EMM offers a Unibus interface for the Micromemory 3000 series.

7. Video Interconnect Panel: A video interconnect panel is available to permit easy and flexible interconnection of video signals. The panel also contains eight adjustable DC voltage sources and a video integrator for use with the special effects generator and video multiplexer.

8. Special Effects Generator(s): The special effects generator produces switching signals for split screen displays. The generator compares x and y scan coordinates with computer controlled set points and will generate a switching signal whenever the scan coordinates are within a designated rectangular space. The designated space can be set to any desired height, width and location with a resolution of one pixel. Thus, the generator has complete flexibility and can even be used to generate a "patch". For future expansion, space will be provided for up to six special effects generators, each of which can generate one "patch". In addition, a special effects interconnect panel will be provided to allow the switching signals to be combined in various ways.

9. Video Multiplexer: An eight channel video multiplexer allows switching between any of 8 video sources. The multiplexer switching is controlled by one or more special effects generators. This capability is adequate to allow up to three "patches" to be overlaid with complete and arbitrary control over the luminance of all eight possible combinations of the three binary variables.

The prints describing these components in more detail are given in Appendix I.

IV. Random-Dot Textures (with S. Purks)

Some time ago, Julesz (1962) proposed that two textures created by random-dot technic...s could not be discriminated if they differed only in their 3rd or higher nth order statistic. We have continued these studies and have found several examples where 4th and even higher nth order strings are discriminable, thus refuting Julesz's original conjecture. An example of one such texture is given in Fig. 5.

We are att..mpting to analyse this type of texture pattern to determine the basis for discrimination. In particular, can we relate the difference in any way to a spatial frequency analysis performed by the visual system. Clearly, the length of runs of black or white areas is also important, but we have not yet resolved the relation between run length and spatial frequency. Our final analysis should also provide some insight to the basis for recognizing texture gradients of the kind depicted by Figure 1.

Figure 5

Two different strings differing only in their 4th order are juxtaposed. The difference between the left and right halves is visible, contrary to earlier proposals about strings differing only in higher order statistics.

V. Texture (Flow) Gradients (with J. Marroquin)

A few years ago, Glass and Perez (1973) described some surprising perceptions of flow created by random dot interference patterns. We have been following up this initial report, creating textures from random arrays that appear to "flow". The method is quite simple: a random dot array is generated by the computer, the X,Y position of each dot is stored, and then the new array is transformed and superimposed upon the old. The transformations we have been working with primarily are expansions, rotations and spirals, both in two and three-dimensional space. Our intent is to determine which kind of transformations are visible to the observer, i.e., appear as a pattern of flow or as a texture gradient. Clearly these studies are thus exploring the more complex, high-level processing of the human observer. Together with the previously described experiments on texture discrimination and texture equivalences (or matching), our research effort is thus covering a broad front of texture analysis.

VI. Projections

Texture is one of the primary properties of an object. Like color, texture is a quality which helps the human observer to define and identify objects. Yet we know little about texture perception. The research in progress offers a completely new approach. The most important aspect of the research is that the texture analysing mechanism of the human observer is only four dimensional. Thus, all (one-dimensional) textures may be completely specified in terms of only four primaries. Such a specification will describe all equivalences between textures. This is a non-trivial accomplishment. In the domain of color perception, if it were necessary to describe all colors in terms of its precise wavelength composition, then the transmission of chromatic information would not have become a feasible possibility. The fact that the human observer filters the wavelength spectrum allows us to build economical communication systems for chromatic information. By the same token, if it may be demonstrated that the human observer analyses textures on the basis of only a few filters, then a considerable saving in the transmission of texture information may be gained. This practical benefit far outweighs, but in no way diminishes the further gains that we will achieve in our understanding of the human visual system.

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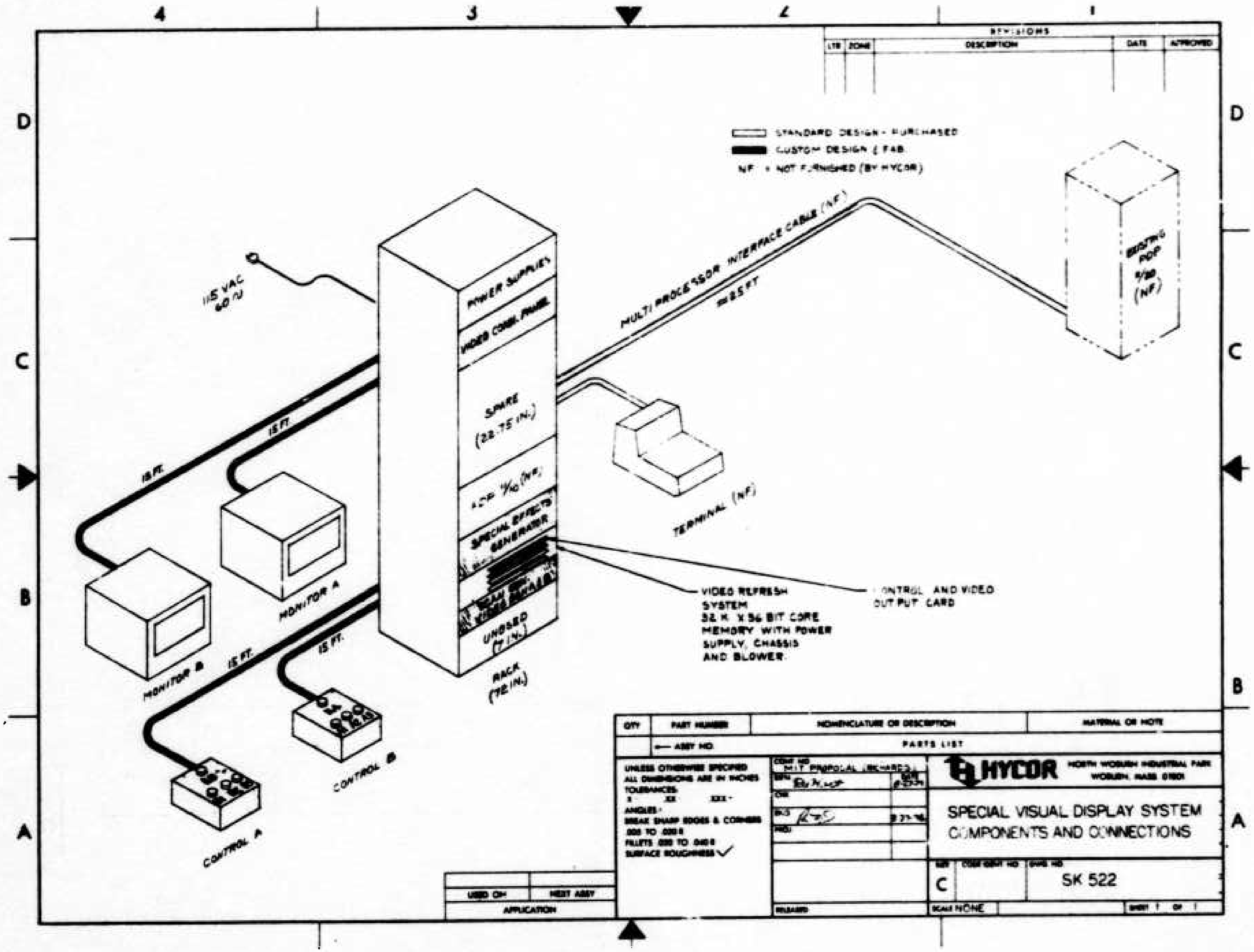
VIII. Appendix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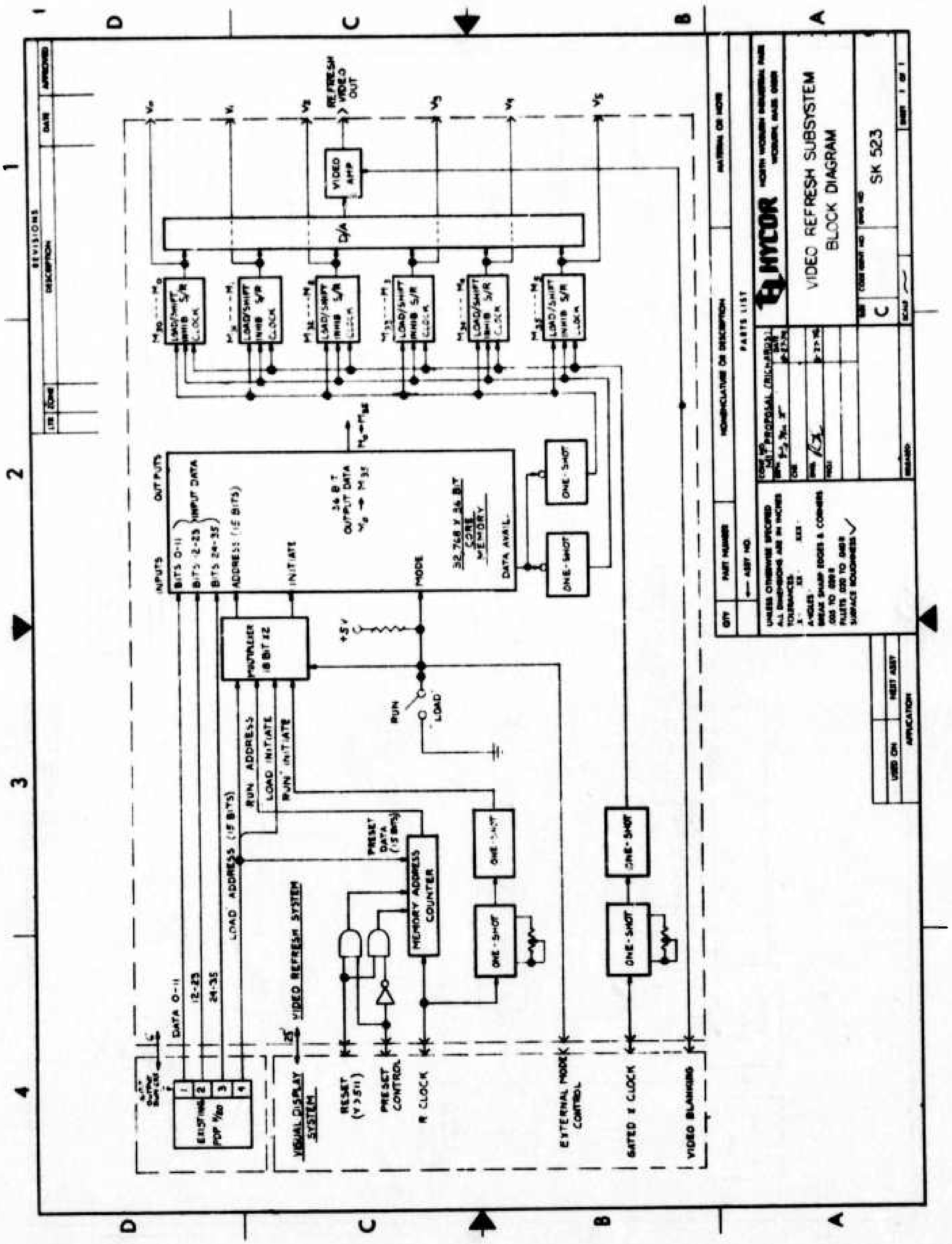
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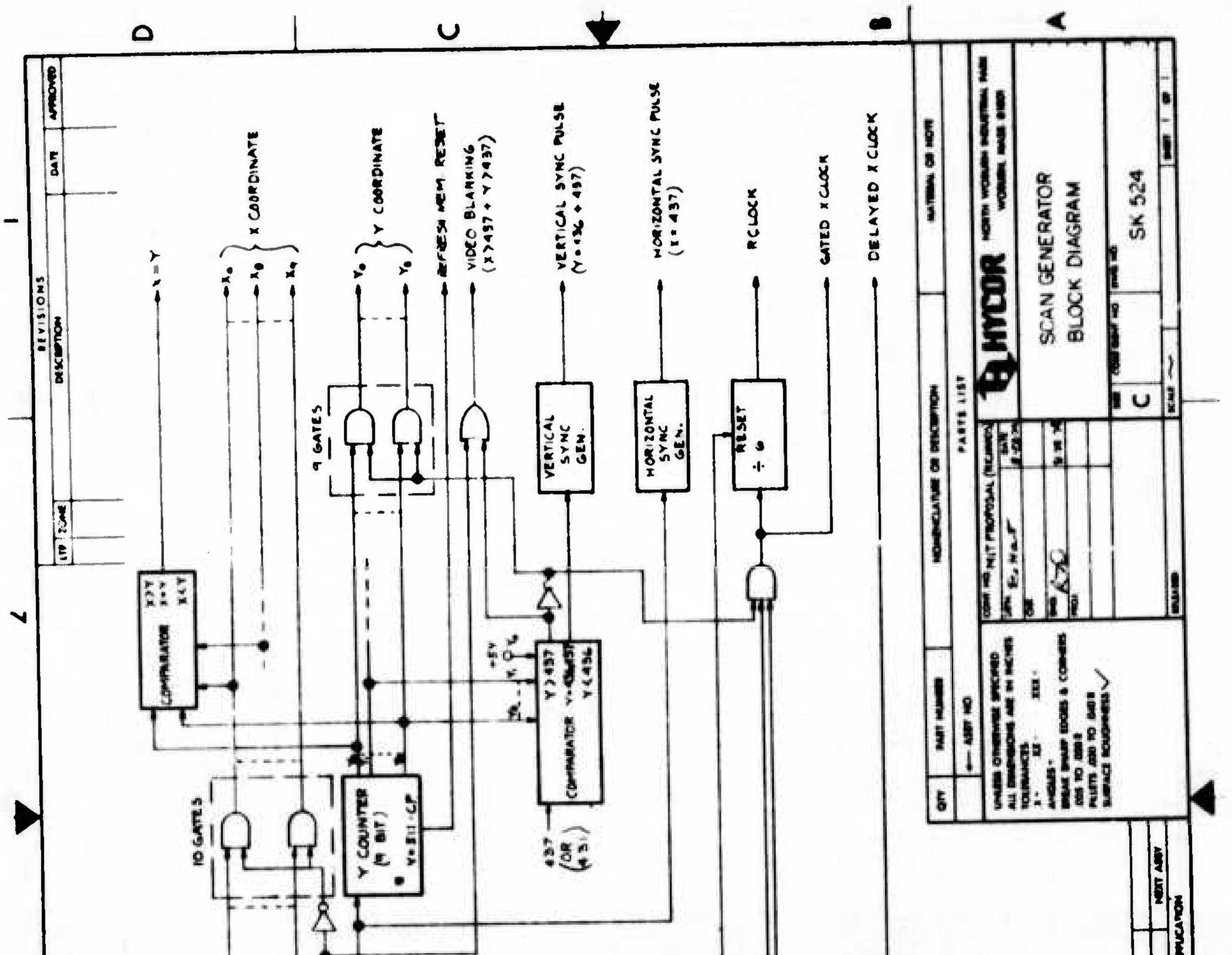

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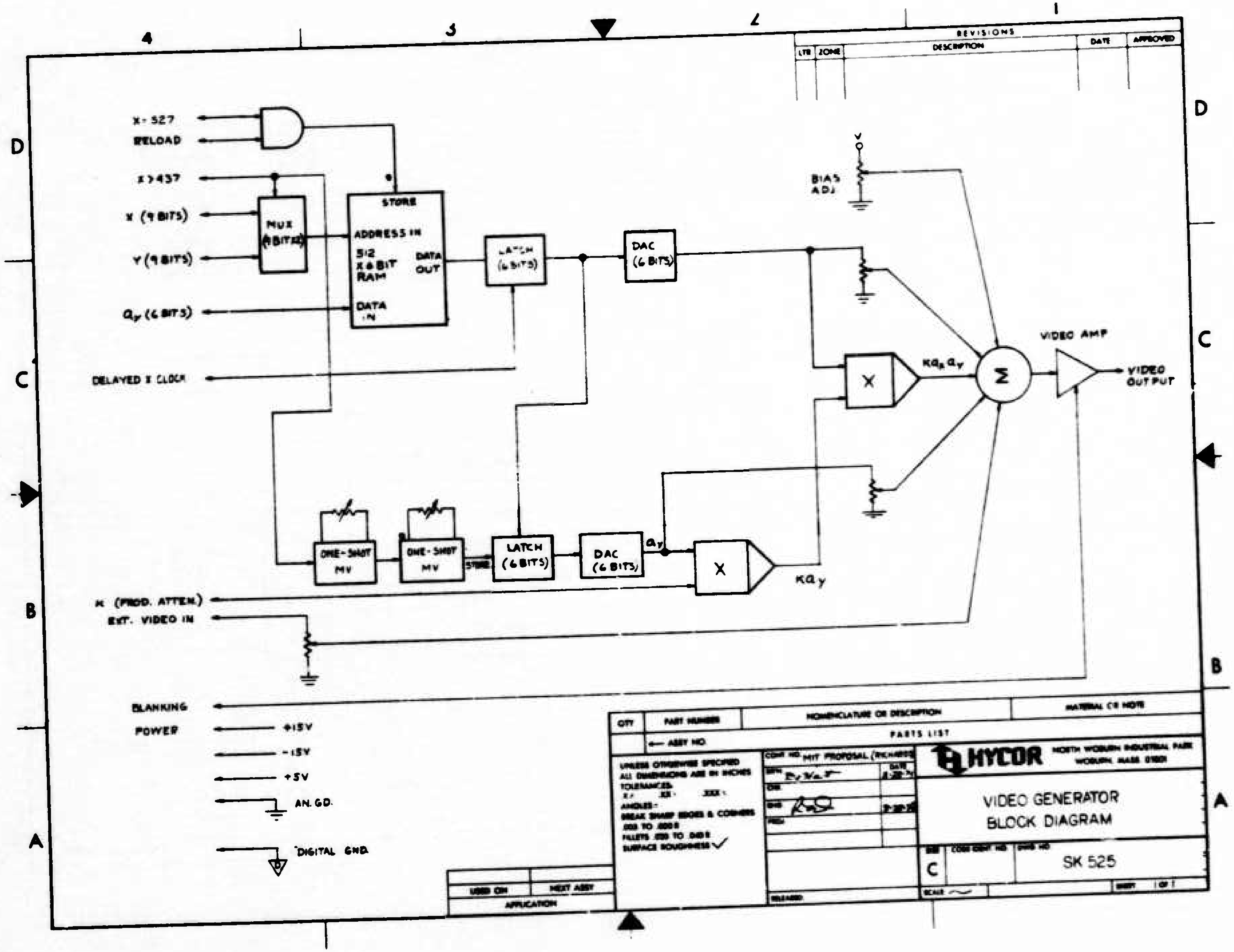
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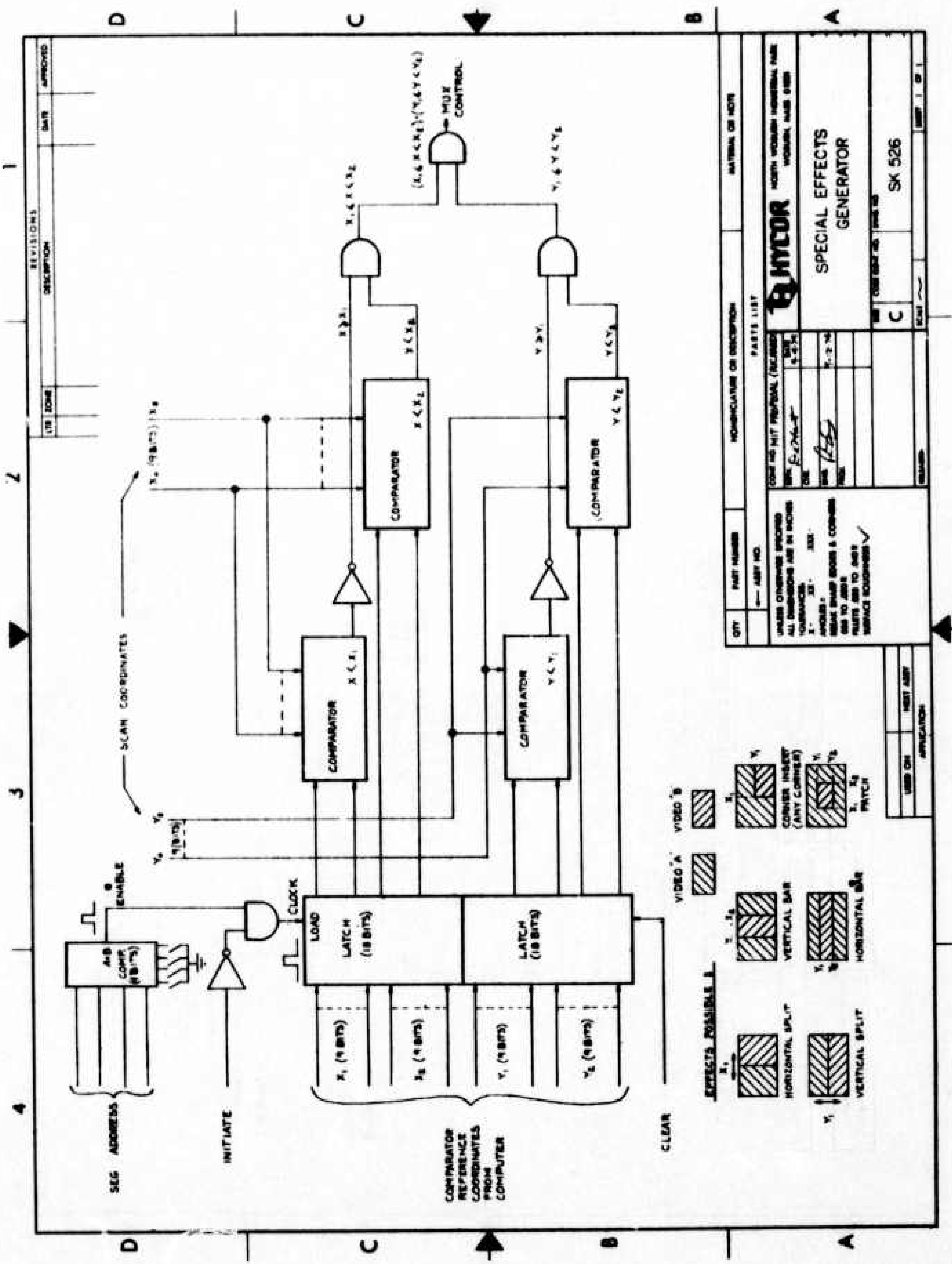
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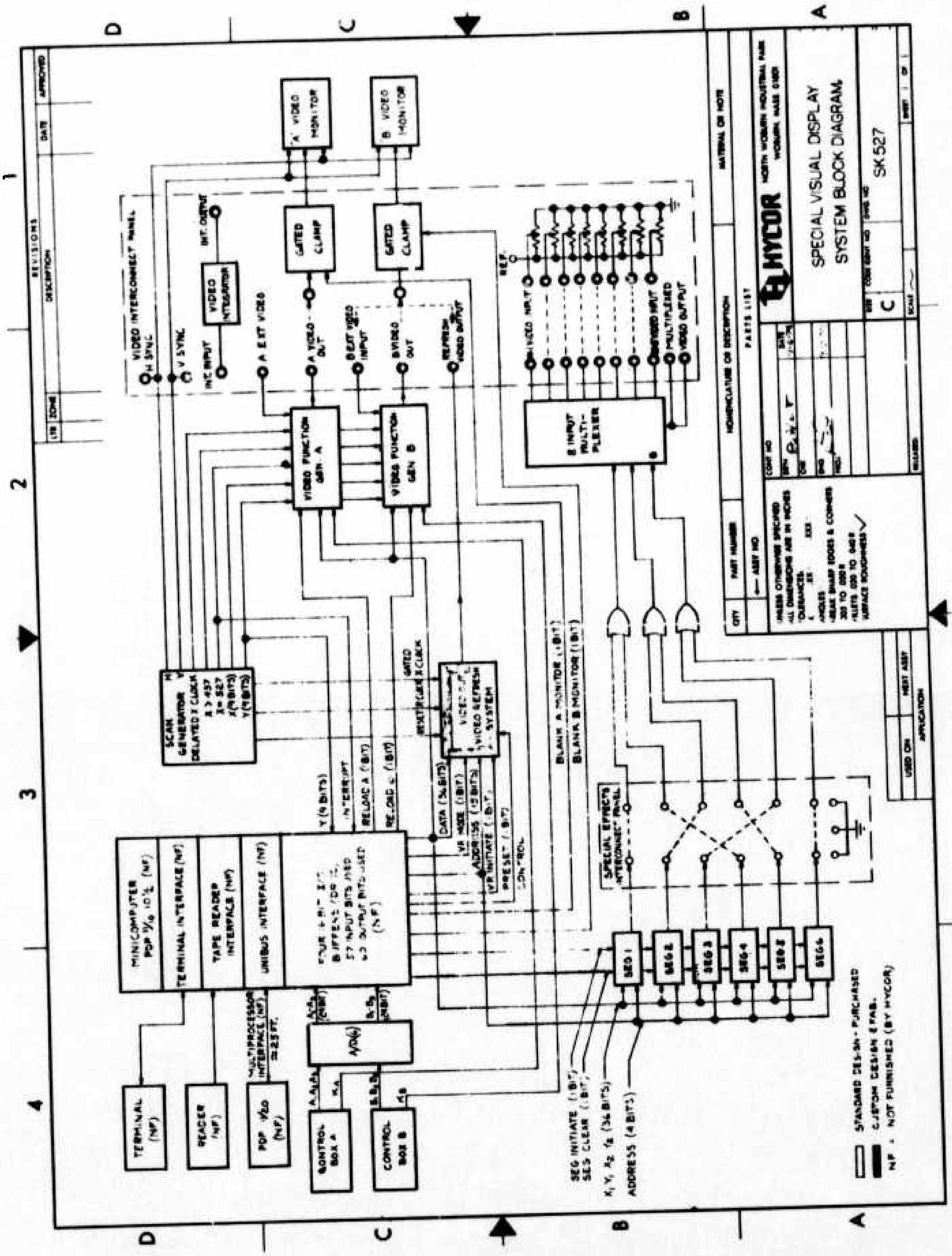
HYCOR
SPECIAL VISUAL DISPLAY SYSTEM BLOCK DIAGRAM
SK 527

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Visual textures may be described completely by their spatial frequency components. For one-dimensional textures whose luminance varies only along the X-axis of the display, the descriptive elements are gratings that have sinusoidal modulations of luminance. Although any arbitrary one-dimensional "blurred" texture may require a very large number of sinusoidal components for its complete physical description, only four components are needed to create a texture that appears the same to the

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) human observer. Thus, the human visual system does not act like a spectral analyser, but rather appears to process spatial frequency information by filtering operations similar to that performed in color vision, at least for one-dimensional texture patterns. In the more general case, textures will have luminance distributions varying in two dimensions (i.e., both X and Y). To test for the minimum number of spatial frequencies required to simulate two-dimensional texture patterns, we are building a new graphics display. The apparatus will permit on-line control of the amplitude (contrast) of the (X,Y) frequency (Fourier) components that make up the texture displayed. Thus, the observer will be able to generate a texture that appears identical to another texture having a different and more complex spatial frequency content. Of interest is the minimum number of spatial frequency components necessary to simulate all two-dimensional textures. If we find, as we did for one-dimensional textures, that only four spatial frequency components are necessary, then we may proceed to design a scheme for transmitting visual information about textures that offers a considerable saving in channel capacity.