APPLICATION OF NONLINEAR ENCODING TO PICTURE TRANSMISSION

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Summary

The process of converting nonlinear analog signals to linear digital signals is a type of companding. This process of companding consists of compressing or expanding the dynamic range at the transmitter and restoring the original levels at the receiver. In telephony it is used to account for differences in speakers' voices. A loud voice will not overdrive the channel, yet a soft voice can be heard.

In image transmission and processing, companding is even more important because of the nature of image forming. Both natural and photographic image formation are multiplicative processes. In a natural scene, the illumination and reflectance of objects are combined by multiplication to form observable brightness. Since this combining is a nonlinear process, it is important to transform the output to a linear signal at the earliest possible point in the transmission. If linearizing is not done, noise will affect the dark portion of the picture much more than the bright areas.

Companding can be accomplished in many ways either by analog or digital method. The most common analog method is the use of log amplifiers with nonlinear amplitude gain. The most common digital technique is nonlinear encoding which performs the companding while the analog signal is being converted to digits.

This companding process, when used on the output of a photo scanner, can be used to improve the transmission and reconstruction of digital pictures.

Scanning Processes

If a standard 16-step, equal-perceptibility curve, modified to provide smaller, low-density increments, is used as a reference input to the encoder, the results of nonlinear encoding curve can be seen in the lower left of Figure I with the lowest voltage level representing a reflection density of 2.10 for reference black. Voltages below this value may be used for various synchronization signals (usually referred to as blacker than black) or may be offset to represent minimum signal.

The amplitude of the steps at low signal, or the dark portion of a picture, are extremely small and a small amount of noise can cause an actual change of density by several steps. This curve represents an approximation as to how the eye actually sees. Notice that the curve is not purely a log function in that the steps get smaller again at the white end of the scale. For this reason, a log amplifier is not a good solution to the problem, although it will help.

Nonlinear A/D Converter

If a linear, four-bit, analog-to-digital converter is used, the linear output A shown in the companded output section will not be obtained. This anomaly is true because only sixteen equal quantum levels are available and any value falling between these values will be that of the lower quantum level. Density steps I through 5 will all fall in the first quantum level, and there will then be only 10 density levels in the digitized output. Density steps 13 and 14 will each occupy three quantum levels.

The simplest solution to the problem is the use of a nonlinear analog-to-digital converter.

By matching calibration curve B of the encoder to that of equal perceptibility inputs, each gray level can be represented by one quantum level (curve B of the companded output). This is actually a compression of the middle portion of the curve with an expansion of the ends of the curve.

Many different ways can be used to make the encoder operate in this manner. Probably the easiest would be a nonlinear comparison ladder matched to this curve. If amplifiers are used for different bits, the gain of these amplifiers could be varied to match the curve. Another method is to store the curve in a memory and use it to provide the reference voltage in the A/D process. The advantage of the latter method is that several programs could be stored and different companding curves used to accomplish different requirements. For instance, if one wishes to enhance the dark portions of the picture, (that is, see into shadows,) calibration curve C could be used. If it were determined, as in the case of the moon's surface, that very little highlight exists, (that is, everything is gray with little dark or bright signals), calibration curve D could be used effectively to expand density step 4 through 13 to 16 quantum levels.

In cases of remote operation the values for different programs could be stored in "read only" type memories and the desired curve could be commanded depending on the requirement at a given time. In photography, this process is known as gamma correction and, in effect, it compresses or expands the dynamic range of film so that one can see into shadows or bright areas.

Naturally, on the receiver end of the transmission system the reverse of this process is used so the companding curve can be matched to that of the gamma curve for the film to be used.

Source Encoding

The above discussion shows the importance in companding regardless of whether redundancy reduction is used or not. However, when a reduction algorithm is used, the value is even more important. Examining the photographs in Figures 2 and 3 will bear out this fact.

Figure 2 was encoded with a linear A/D converter to 8 bits and reduced from 2 x 10^6 elements, using the Step Method (zero-order compression algorithm) to 2.2 x 10^4 elements. The tolerance was 12 levels in 256 or 4.7 percent. There are 2.664 x 10^6 bits in the picture. The reduction was to 1.33 bits/element. If one looks carefully in the dark areas, large amounts of streaking can be seen. This is particularly true on the right side of the man's head.

In Figure 3 the companding calibration curve shown as curve B in Figure 1 was used in the encoding process. The picture was reduced from 2 x 10^6 elements, again using the Step Method to 2.1 x 10^4 six-bit elements. The tolerance needed to obtain this reduction was only 2 parts in 64 or 3.1 percent. There are 2.1 x 10^6 bits in this picture. The reduction was to 1.06 bits/element, which is considerably less than in Figure 2.

As noted in Figure 3, the quality is far superior to Figure 2 even though Figure 2 is an eight-bit picture and has more nonredundant samples. The reason for this is that the errors due to the reduction were all made in the dark end of the scale in Figure 2, due to the small steps. In Figure 3 the steps have been expanded to be equal over the entire range and, therefore, the errors made are distributed over the entire picture and do not cover more than one gray-scale step.

Further importance in companding can be seen by examining an oscillogram of the uncompanded signal obtained by scanning a 15-step, equal-perceptibility, gray scale. This oscillogram (Figure 4) also shows the effect of different kinds of noises produced in any kind of scanning systems.

Definition of Signal-to-Noise Ratio

To understand this noise and its effect on reduction algorithms better, a description of signal-to-noise (S/N) and Dynamic Range (DR) is needed. The interpretations of these terms often differ with different kinds of users. In general, the noise in any scanner or photographic process varies with the signal, whereas in an "ordinary" electronic amplifier the noise is generally constant. As darker objects are scanned, the signal current decreases to a point when it will be masked by a constant background noise somewhere in the rest of the equipment. A noise that varies with the amplitude of the signal is called multiplicative noise; and noise independent of the signal amplitude is called additive. Additive noise is sometimes called ordinary noise, and multiplicative noise, extraordinary noise.

The following description of S/N and DR is generally accepted when referring to the performance of scanning systems.

Because of the multiplicative nature of noise in a scanning system, the definition of S/N is made more difficult than it would be in common electronic usage where it is simply defined as the ratio of the rms signal to the rms noise. For the purposes of this paper, S/N is defined (Figure 5) in the same manner as it is in television: the maximum signal (S) divided by the rms noise (N_m) in the presence of this maximum signal or $S/N = \frac{S}{N_m}$

The DR is defined as the maximum signal (S) divided by the noise (N_o) when no other signal is present or:

$$DR = \frac{S}{N_o}$$

These definitions for S/N and DR are selected because they show

1) the smallest signal increment that can be detected in the presence of the maximum signal; and

2) the smallest signal increment that can be detected in the presence of minimum signal.

Using the definitions above in a system with purely additive noise, DR will equal S/N, while in a system with multiplicative noise, as in the electron beam recording system, DR ideally will equal 2 S/N measured in dB. In practice, DR will be less because of the presence of the additive noise in the rest of the equipment.

The multiplicative noise of Figure 4 is much worse than the additive noise. The S/N of this scanner is about 27 dB while the DR is about 42 dB.

If the data were companded, the whites would be compressed, thus reducing the amplitude of the multiplicative noise. Companding would then improve the signal-to-noise ratio. When the black is expanded, it will increase the additive noise; however, since the dynamic range is much better than the signal-to-noise, the increase will not be harmful. In general, the noise would then be more evenly distributed and affect the entire picture rather than just the dark area.

Effects of Signal-to-Noise

Signal-to noise ratio as defined above is the limiting factor in the amount of reduction possible. Streaking seen in the reduced pictures (Figures 2 and 3) is a result of this noise. The noise is averaged out in the analog case or when many samples are transmitted; however, when reducing the data by redundancy reduction, the noise appears as signal and the peaks are transmitted. One must transmit all the noise peaks (above the tolerance) or the reconstructed waveform differs widely from the original waveform. Thus, many nonredundant samples are needed just to transmit the noise. The noise peaks also tend to cause a shifting of edges from line to fine and thus produce the streaking effect.

If a signal-to-noise ratio of better than 60 dB could be obtained, the streaking cannot be seen and the amount of reduction greatly increases.

The scanner that produced Figures 2 and 3 had a signal-to-noise ratio of about 30 dB before companding. The rms value of the multiplicative noise was about 0.4 volts. Companding reduces this to about 0.2 volts and increases the effective signal-to-noise ratio to about 35 dB.

Facsimile Camera

In camera systems where the image is formed a line at a time directly on a photo diode, the signal-to-noise ratio will be much better than a scanner working from reflectance, where the grain of the paper and any imperfection is noise. This type of scanning will increase the amount of reduction possible and improve the quality of the reduced pictures.

Conclusion

The importance of companding at the earliest possible moment cannot be overstressed. If a little system noise gets into a signal before companding, it is expanded and cannot be removed. It is suggested that the A/D converter and nonlinear encoder be placed inside the camera, almost as an integrated part of the photo diode. This configuration will keep the system noise to a minimum and can better match the optics of the camera. Further, it is impossible to separate the imagery and the data processing and they should be handled as one problem.

Before any nonlinear encoding network is designed it is strongly recommended that the optics be included in the overall problem, and a careful study of the noise situation be made.

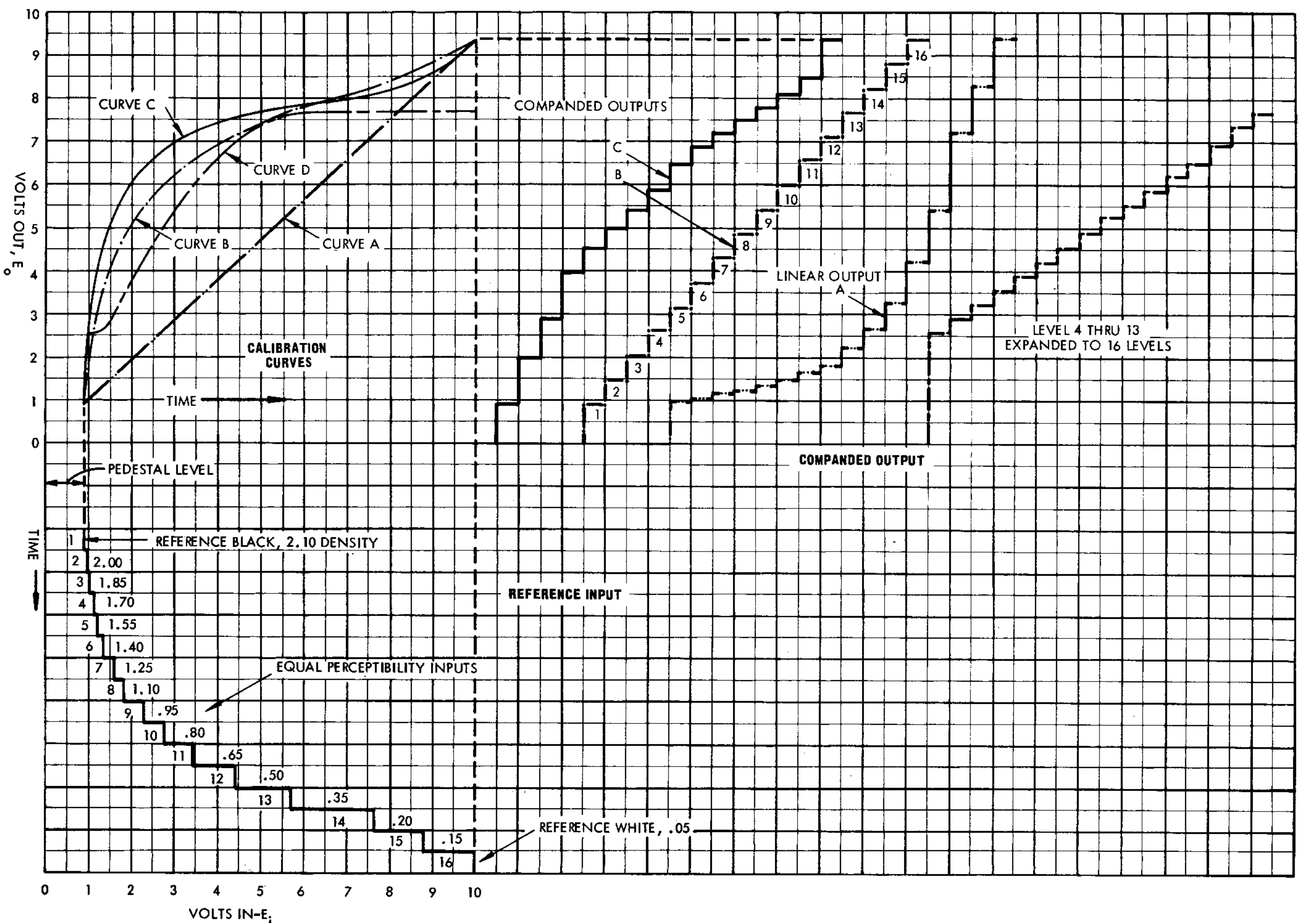


Figure 1 - Results of Nonlinear Encoding

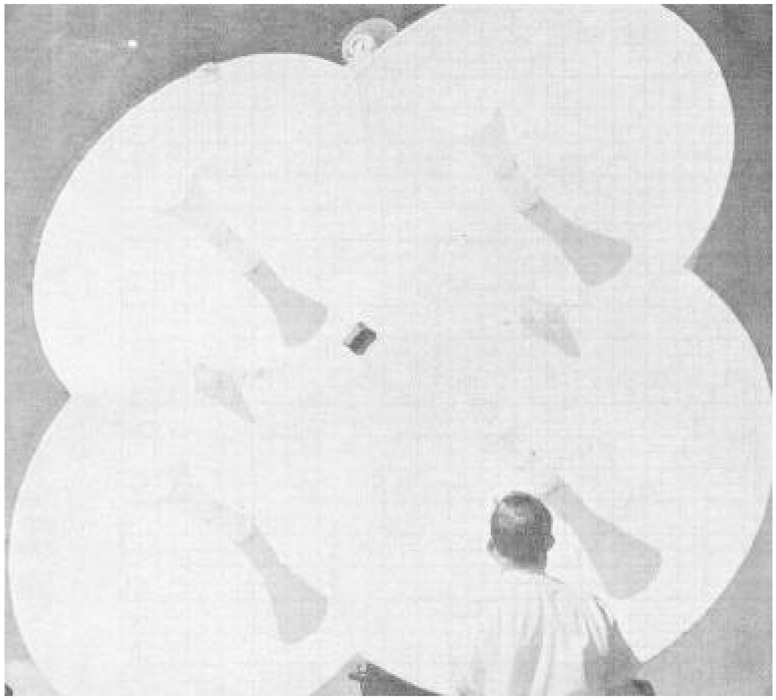


Figure 2 - Linear Encoded Digital Picture
2,000,000 Elements - 16,000,000 Bits
Reduced by Step Compression Algorithm - 12 Levels in 256 or 4.7%
Reduced to 220,000 12-Bit Nonredundant Elements
Element Reduction (E_r = 9-09
Bit Reduction (B_r = 6.06
1.33 Bits/Element

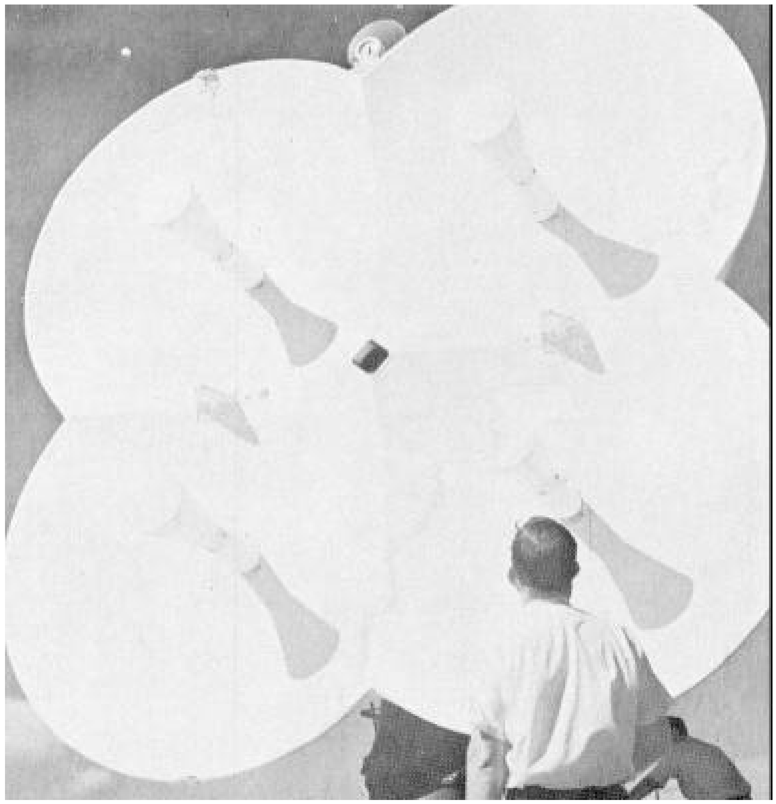


Figure 3 - Nonlinear Encoded Digital Picture
Companded to Match Standard Equal Perceptibility Curve
2,000,000 Elements - 12,000,000 Bits
Reduced by Step Compression Algorithm, 2 Levels in 64 or 3.1 %
Reduced to 210,000 10- Bit Nonredundant Elements
Element Reduction (E_r = 9.52
Bit Reduction (B_r = 5.71
1.06 Bits/Element

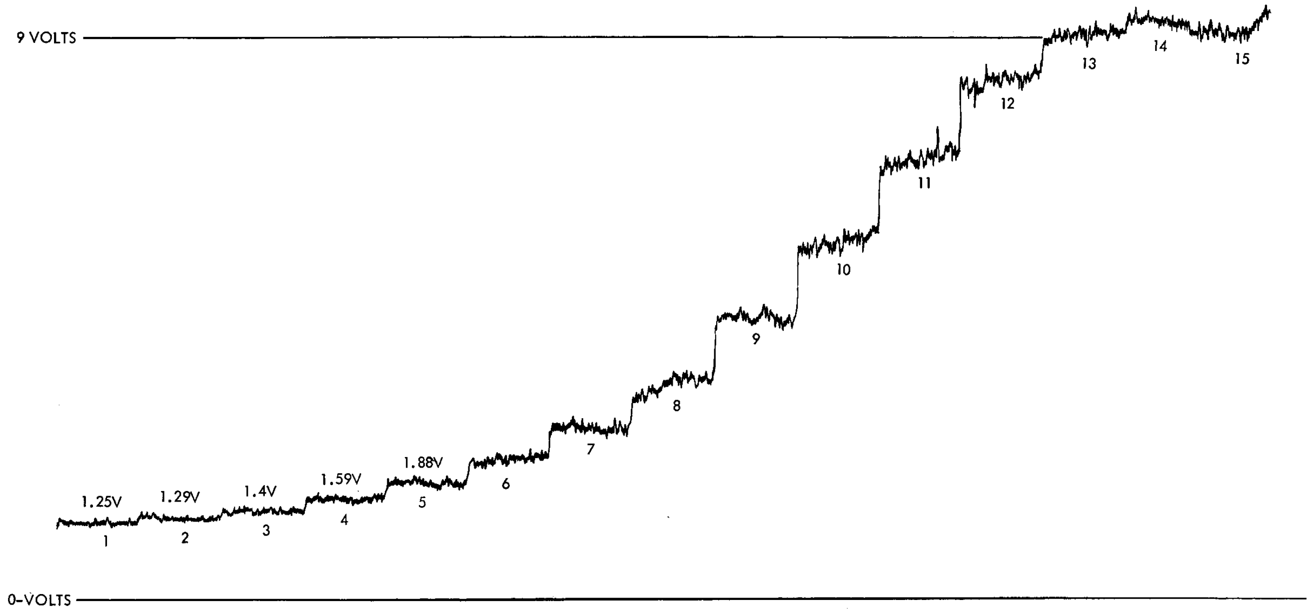
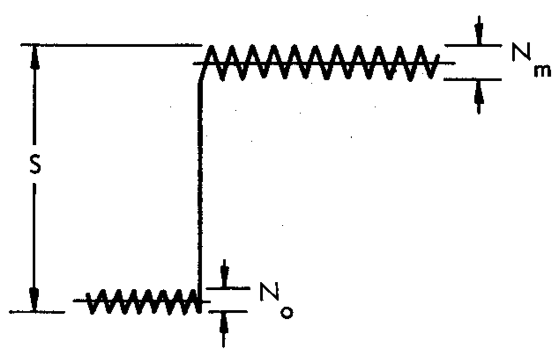


Figure 4 - Oscillogram of Equal Perceptibility Scale



$$S/N = \frac{\text{Peak Signal}}{\text{Noise at max. signal}} = \frac{S}{N_m} \qquad DR = \frac{\text{Peak Signal}}{\text{Noise at min. signal}} = \frac{S}{N_o}$$

Figure 5. Definitions of S/N and DR